RAA 2017 Vol. **17** No. **3**, 24 (16pp) doi: 10.1088/1674–4527/17/3/24

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Research in Astronomy and Astrophysics

Physical properties of lunar craters

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Received 2016 August 11; accepted 2016 November 25

Abstract The surface of the Moon is highly cratered due to impacts of meteorites, asteroids, comets and other celestial objects. The origin, size, structure, age and composition vary among craters. We study a total of 339 craters observed by the Lunar Reconnaissance Orbiter Camera (LROC). Out of these 339 craters, 214 craters are known (named craters included in the IAU Gazetteer of Planetary Nomenclature) and 125 craters are unknown (craters that are not named and objects that are absent in the IAU Gazetteer). We employ images taken by LROC at the North and South Poles and near side of the Moon. We report for the first time the study of unknown craters, while we also review the study of known craters conducted earlier by previous researchers. Our study is focused on measurements of diameter, depth, latitude and longitude of each crater for both known and unknown craters. The diameter measurements are based on considering the Moon to be a spherical body. The LROC website also provides a plot which enables us to measure the depth and diameter. We found that out of 214 known craters, 161 craters follow a linear relationship between depth (d) and diameter (D), but 53 craters do not follow this linear relationship. We study physical dimensions of these 53 craters and found that either the depth does not change significantly with diameter or the depths are extremely high relative to diameter (conical). Similarly, out of 125 unknown craters, 78 craters follow the linear relationship between depth (d) and diameter (D) but 47 craters do not follow the linear relationship. We propose that the craters following the scaling law of depth and diameter, also popularly known as the linear relationship between d and D, are formed by the impact of meteorites having heavy metals with larger dimension, while those with larger diameter but less depth are formed by meteorites/celestial objects having low density material but larger diameter. The craters with very high depth and with very small diameter are perhaps formed by the impact of meteorites that have very high density but small diameter with a conical shape. Based on analysis of the data selected for the current investigation, we further found that out of 339 craters, 100 (29.5%) craters exist near the equator, 131 (38.6%) are in the northern hemisphere and 108 (31.80%) are in the southern hemisphere. This suggests the Moon is heavily cratered at higher latitudes and near the equatorial zone.

Key words: Moon, meteorites, meteors, meteoroids — planets and satellites: surfaces

1 INTRODUCTION

Many investigations have been done on lunar craters like depth-diameter ratio, shape and age of craters, type of craters, morphology, etc. Craters are formed as a consequence of the impact of meteorites, comets and other celestial objects on the surface of the Moon. Shape and structure of these craters depend on the density, diameter and direction of entry of the impacting object (impactor). It has been observed that lunar craters are largely circular. The shape of a crater will be circular if material flies out in all directions as a result of the explosion caused by the impact. The shape of the associated impactor is not of much significance. It has been noticed that generally the impactors are not spherical in shape. Craters in the solar system are visible on many solid planets and moons. However, Mercury and our Moon are heavily covered with craters, perhaps because they both do not have an atmosphere. Small bowl-shaped craters with smooth walls are mostly simple and have diameters less than 15 km. On the other hand, complex craters have diameters larger than simple craters and their features are also more complicated. Larger craters having diameters more than 15 km display features like terraces, central peaks and multiple rings. The size and shape of a crater and the amount of material excavated on a given planet depend on the velocity and mass of the impacting body as well as the geology of a planet's surface. Craters will be larger in size if the impactor enters faster or has greater mass. Typically, celestial objects/materials entering with a velocity of more than 20 kilometers per second which hit the Earth produce a crater that is approximately 20 times larger in diameter than the impacting object. On the other hand, impactors will strike at lower speeds on smaller celestial bodies like Mercury and Moon because they have less gravitational "pull."

Craters are formed as a consequence of collision of two objects at high velocity. One of the colliding objects, small in size, known as the impactor is usually destroyed during impact and a crater develops on the larger object, known as the target. The size and structure of the crater generated on the target are largely controlled by the size, composition and velocity of the impactor (Dutton 1999).

The physical properties, viz. size, composition and velocity, of the impactors are different from each other. The size ranges from microns to hundreds of kilometers in diameter, while the composition varies from ice to rock containing iron or metal alloys, and the velocity typically varies in the range 10 to 70 $\mathrm{km\,s^{-1}}$. On the other hand, if the target's (the Moon in our study) material strength is weaker, the resulting crater will be larger. In addition to the impactor's physical properties, the target's own properties also play a key role in governing the shape of the craters. For example, the target's pre-existing geological structure and its gravitational pull control the shape of the crater. In the context of this physical process, we may conclude that formation of the crater involves an energy transfer mechanism. The kinetic energy of the impactor is transferred into heat so as to fracture and displace target rocks. It is estimated (Dutton 1999) that a 1 km diameter stony iron spherical asteroid with a density of 3000 $\mathrm{kg\,m^{-3}}$, impacting at a velocity relative to the target of 20 $\mathrm{km\,s^{-1}}$, releases 3.2×10^{20} J of kinetic energy.

Previously, Williams & Zuber (1998) carried out measurement and analysis of lunar basin depths employing data from Clementine altimetry. The depth to diameter relation of the lunar craters was investigated by Pike (1974, 1977). Study of the topography of a few large craters was conducted by Elachi et al. (1976) while scaling of impact melting and crater dimension was done by Cintala & Grieve (1998). Recently, significant studies were conducted, viz. study of hydrogen mapping of the lunar South Pole (Mitrofanov et al. 2010); transition from complex to peak-ring basin on the Moon (Baker et al. 2011); and polar hydrogen deposits on the Moon (Feldman et al. 2000).

Chandrayaan-1 was launched successfully on 2008 October 22 and one of its instruments, the Moon Mineralogy Mapper, demonstrated the presence of water on the North Pole of the Moon (Pieters et al. (2009)). However, this feature is seen as widely distributed absorption appearing strongest at the cooler high latitudes and at several fresh feldspathic craters on the Moon. Therefore, investigation of the distribution of craters as a function of latitude as well as longitude is important.

Craters are being formed everyday on planetary objects. The International Astronomical Union (IAU) has been including crater data in its Gazetteer from time to time. In this paper, craters which are included in the IAU Gazetteer of Planetary Nomenclature are called known craters while those not included are called unknown craters (*planetarynames.wr.usgs.gov*).

Studies related to measurement of size and depth of lunar craters have been done by several investigators: using the shadow method Young (1984) analyzed 100 known craters, while employing ERDAS Imagine software Aasim & Bahuguna (2014) studied 80 craters, using ESRI ArcGIS 10.1 software Krüger et al. (2015) studied 540 known craters, and Zhang et al. (2016) analyzed 180 known craters employing the AdaBoost method. On the other hand, Moutsoulas & Preka (1980) studied morphological characteristics and depth to diameter ratio for 1933 known lunar craters. However, we found that either no study or very little study has been carried out about unknown lunar craters and particularly the causal mechanisms of those known or unknown craters which do not follow the depth-diameter linear relationship. The longitude and latitude distribution of craters on the Moon has also been not studied in greater detail. In this paper, we attempt to address these issues by employing the Lunar Reconnaissance Orbiter Camera (LROC) data set.

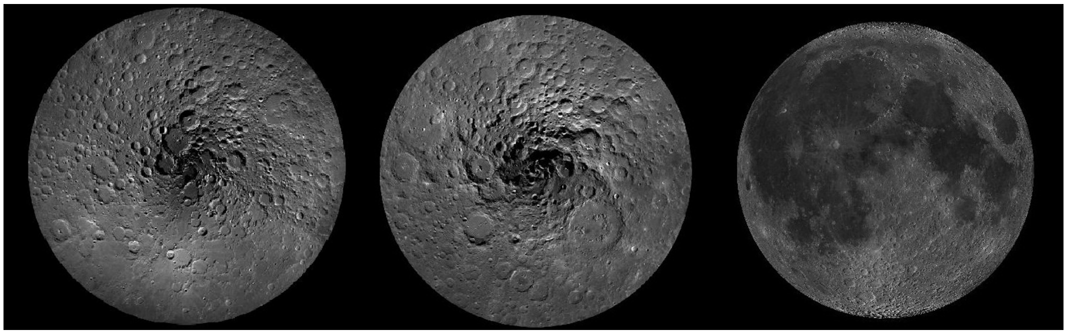

Fig. 1 Image of lunar North (*left panel*) and South (*middle panel*) Poles, and near side (*right panel*) obtained by LROC.

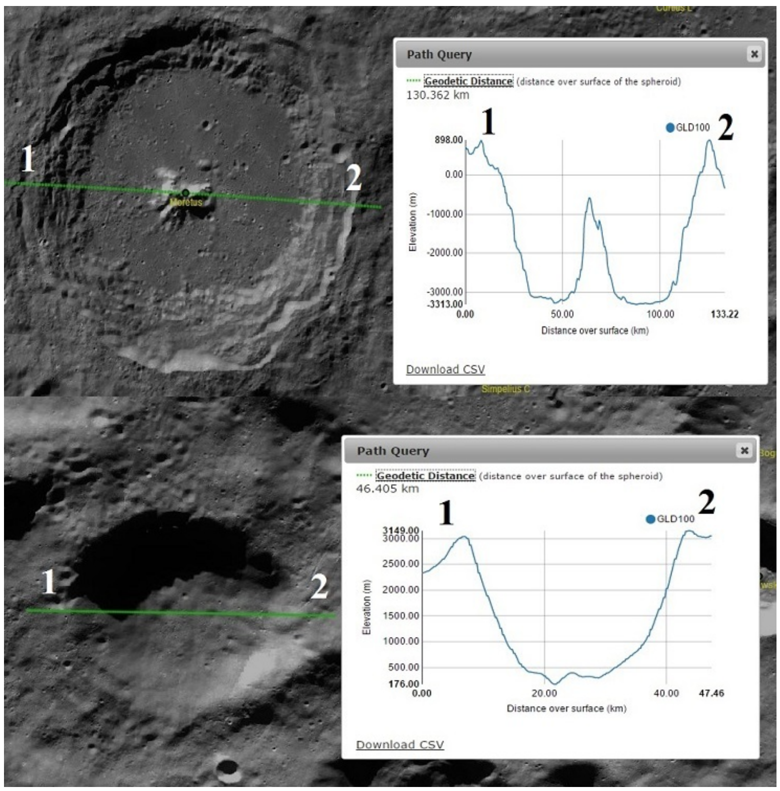

Fig. 2 Image of the crater Moretus (*top panel*) near the South Pole (70.64° S; 6.01° W) and an unknown crater (74.31° S; 20.09° E *bottom panel*) on the Moon obtained by LROC. Diameter and depth of Moretus have been measured from the graph (see text) to be 114.54 and 6.12 km respectively, and those of the unknown crater to be 37.9 and 3.73 km respectively. The *green line* represents the diameter revealed from the selection of two end points on the rim (see text).

2 OBSERVATIONS

2.1 Instrument and Data Set

The LROC is a system of three cameras mounted on the Lunar Reconnaissance Orbiter (LRO) that captures high resolution black and white images and moderate resolution multi-spectral images of the lunar surface (Robinson et al. 2010a). LROC also consists of two Narrow Angle Cameras (NACs) to provide 0.5 meter-scale panchromatic images over a 5 km swath, and a Wide Angle Camera (WAC) to provide images at a scale of 100 meters/pixel in seven color bands over a 60 km swath. The Sequence and Compressor System (SCS) supports data acquisition for both cameras (Robinson et al. 2010b). LROC is a modified version of the Mars Reconnaissance Orbiter's ConTeXt Camera (CTX) and

Mars Color Imager (Malin et al. 1999, 2007; Bell et al. 2009). For the current investigation we acquired images from the URL *http://target.lroc.asu.edu/q3*, having resolution of 100 m/pixel.

3 METHODOLOGY

We adopt the following steps to analyze images.

(1) We select images from the link *http://target.lroc.asu.edu/q3* (cf. Fig. 1).
(2) Next we select the position of the Moon to mark the geographical location employing option Change Projection.
(3) In order to select the crater, we mark two end points on the rim of the crater (cf. Fig. 2), and by clicking twice on the same marked points we get a graph/plot, which provides information on depth and diameter of the crater (cf. Fig. 2 - right side). However, in order to obtain the complete data set, viz. depth, diameter, longitude, latitude, etc., we further click on and download the Comma-separated values (CSV) file.
(4) Next, we mark the position of two peak points, observed on the graph, on the Global Lunar DTM 100 m topographic model (GLD100), which gives the difference in their positions. This difference is calculated to obtain an estimate of the diameter.
(5) We also record the value of depth from the graph.

We have also derived diameter from latitude and longitude using the following formula.

$$d = 2r \times \sin \sqrt{\sin^2\left(\frac{\Delta\theta}{2}\right) + \cos\theta_1 \cos\theta_2 \sin^2\left(\frac{\Delta\lambda}{2}\right)}, \quad (1)$$

where d is diameter of the crater, r is radius of the Moon, and θ and λ refer to latitude and longitude, respectively. We convert degrees into radians. The diameter derived employing the above equation is compared with diameter obtained from the graph and found to agree with each other within $\pm 2\%$ error.

The lunar images obtained from LROC can be magnified and the desired location can be analyzed by executing the above steps. Shown in Figure 1 are images taken at the North and South Poles and the near side of the Moon by LROC, which are analyzed by us. Example images of a known as well as an unknown crater are shown in Figure 2.

4 ANALYSIS AND RESULTS

We split up our investigation in three parts: study of known craters, unknown craters, and latitude and longitude distribution.

4.1 Known Craters

The images shown in Figures 1 and 2 have been analyzed by the method described in Section 3. We randomly chose a total of 224 known craters distributed around the North and South Poles as well as near the equator. The data values obtained for each known crater, viz. diameter (D), depth (d), d/D ratio and location, are presented in Table 1. The well known depth to diameter linearity was not observed for all chosen 224 craters. Thus we divided the sample into two parts: those that follow the linearity scaling law and the others that do not follow it. In Figure 3 we show the variation of depth as a function of diameter for 161 craters following the linearity law and find a correlation coefficient of $\sim$0.84. In Figure 4 we show the same plot but as a histogram, which reveals, by and large, that the formation mechanism of such craters is similar, i.e., craters with increasing depth are formed by impactors with progressively larger diameter and higher density material.

On the other hand, we found that 53 craters do not exhibit linearity. In these craters, either depth was not increasing with diameter or vice versa. This result is shown in the form of a histogram in Figure 5. These craters appear to follow different formation mechanisms. It seems that these craters were formed either by objects bigger in size but with low density material, such as silicon or ice, or by objects with a conical shape having high density material, viz. iron or tungsten rock, or else by objects with bigger size and high density.

4.2 Unknown Craters

We also analyzed 125 unknown craters (not identified so far by anyone and for which, to the best of our knowledge, no name has been given), ranging in diameter between < 1 to 40 km. The measured diameter (D), depth (d) and the location of each unknown crater are presented in Table 2.

However, in this case, like for known craters, we only found 78 craters following the d/D linearity scaling law. The remaining 47 craters do not exhibit linearity in the d/D plot. Shown in Figure 4.2 is the plot

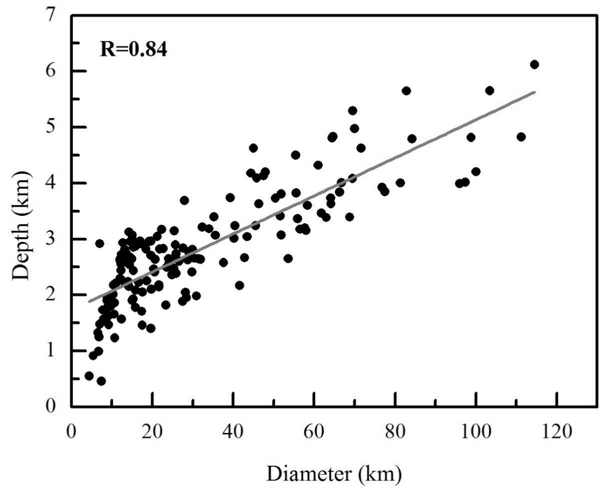

Fig. 3 The variation of depth as a function of diameter of known craters. Correlation coefficient (R) is about 0.84.

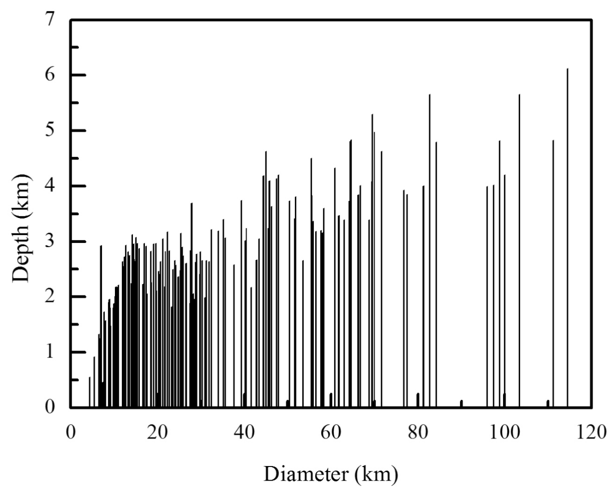

Fig. 4 Histogram showing known craters following the d/D linearity law.

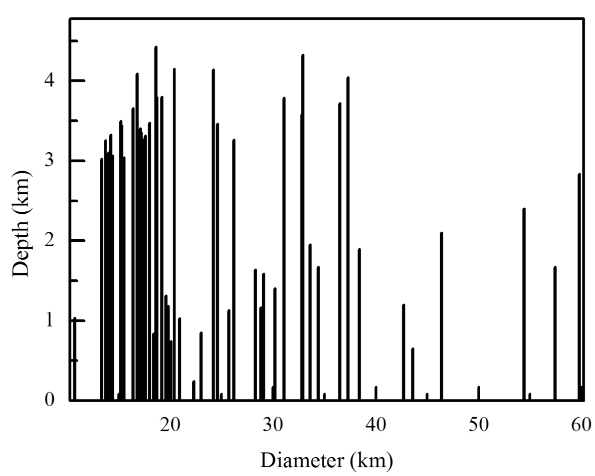

Fig. 5 Histogram showing known craters not following the d/D linearity law.

Table 1 Observations for Known Craters

Sr. No.	Crater Name	Average Latitude	Average Longitude	LROC Diameter (D) (km)	LROC Depth (d) (km)	Calculated Diameter (D) (km)	d/D	Pole
1	Avogadro D	63.84	170.11	19.60	2.96	19.53	0.15	North
2	Roberts Q	68.38	177.05	19.60	2.71	19.51	0.14	North
3	Gamow B	66.28	149.14	25.30	2.48	25.29	0.10	North
4	Kirkwood Y	71.68	–158.49	18.60	2.25	18.56	0.12	North
5	Stebbins U	64.92	–147.1	44.40	4.18	44.26	0.09	North
6	Seares B	75.19	150.37	26.60	2.61	26.58	0.10	North
7	Dugan J	61.44	107.43	13.20	2.81	13.21	0.21	North
8	Nother E	66.76	–105.32	46.30	3.63	46.28	0.08	North
9	Schwabe F	66.45	50.67	20.70	2.64	20.69	0.13	North
10	Schwabe G	65.50	41.43	15.30	2.86	15.27	0.19	North
11	Maigno A	64.80	29.76	15.80	2.87	15.78	0.18	North
12	Fontenelle A	67.61	–15.27	21.60	2.15	21.60	0.10	North
13	Paneth W	64.72	–101.6	28.40	1.96	28.37	0.07	North
14	Lovelace E	82.03	–94.18	22.70	2.83	22.67	0.12	North
15	Brianchon B	72.17	–87.53	31.90	2.63	31.89	0.08	North
16	Desargues L	69.50	–81.65	13.30	2.21	13.28	0.17	North
17	Cleostratus A	62.68	–77.23	35.60	3.07	35.64	0.09	North
18	Pascal J	72.18	–68.66	14.40	2.64	14.36	0.18	North
19	Mouchez B	78.35	–22.74	7.70	1.73	7.67	0.22	North
20	Barrow A	70.57	3.75	28.80	2.63	28.79	0.09	North
21	Kirkwood	68.32	–155.4	69.52	5.29	69.53	0.08	North
22	Hippocrater	70.27	–148.53	61.81	3.46	61.83	0.06	North
23	Tikhov	61.64	169.87	81.31	4.00	81.29	0.05	North
24	Ricco	75.01	176.84	64.62	4.83	64.60	0.07	North
25	Thiessen	74.83	–165.96	66.75	4.01	66.77	0.06	North
26	Heymans	74.70	–147.43	51.80	3.07	51.82	0.06	North
27	Pointsot	78.87	–141.05	66.27	3.84	66.29	0.06	North
28	Froelich	79.97	–107.32	56.51	3.18	56.53	0.06	North
29	Erlanger	86.99	25.65	10.60	2.17	10.60	0.20	North
30	Gore	86.18	–61.37	9.80	1.81	9.80	0.18	North
31	Carpenter	69.54	–50.51	60.93	4.32	60.91	0.07	North
32	Philolaus	72.20	–33.82	69.46	4.08	69.48	0.06	North
33	Dugan X	67.83	97.54	14.60	2.67	14.40	0.18	North
34	Cusanus	71.79	66.46	63.01	3.39	63.00	0.05	North
35	Hayn A	62.95	70.41	53.54	2.65	53.52	0.05	North
36	Strabo	61.91	53.73	57.70	3.20	57.71	0.06	North
37	Scoresby	77.74	15.45	55.40	4.50	55.40	0.08	North
38	Fontenelle	A 67.61	–16.68	21.60	2.18	21.59	0.10	North
39	C. Mayer	63.28	16.03	40.47	3.24	40.43	0.08	North
40	C. Mayer E	61.16	15.68	12.00	2.29	12.01	0.19	North
41	Meton W	67.46	17.17	8.00	1.57	7.98	0.20	North
42	Timaeus	62.94	0.12	31.30	2.65	31.28	0.08	North
43	Baillaud E	74.33	35.04	14.90	2.65	14.90	0.18	North
44	Thales G	61.49	45.36	10.50	1.65	10.48	0.16	North
45	Roberts M	67.66	–172.34	45.80	4.09	45.81	0.09	North
46	Emden M	60.78	–177.31	27.90	3.69	27.88	0.13	North
47	Lindblad Y	72.74	–99.56	28.20	2.05	28.19	0.07	North
48	Nother V	68.55	–123.16	25.70	2.90	25.71	0.11	North
49	Heymans T	74.66	–153.84	32.40	3.22	32.39	0.10	North
50	Poinsot K	77.06	–141.08	17.60	2.05	17.60	0.12	North
51	Plaskett H	79.60	–163.13	19.60	1.40	19.63	0.07	North
52	Peterman X	75.03	75.69	9.90	1.87	9.91	0.19	North
53	Peterman Y	75.71	85.86	12.70	2.93	12.68	0.23	North
54	Peterman S	75.31	61.82	9.20	1.47	9.19	0.16	North
55	Peterman B	72.76	63.39	10.70	1.23	10.72	0.12	North

Table 1 — *Continued.*

Sr. No.	Crater Name	Average Latitude	Average Longitude	LROC Diameter (D) (km)	LROC Depth (d) (km)	Calculated Diameter (D) (km)	d/D	Pole
56	Peterman E	72.48	53.3	14.30	2.54	14.31	0.18	North
57	Casanus B	70.11	64.05	20.60	2.42	20.58	0.12	North
58	Arnold M	68.29	43.59	6.70	0.99	6.69	0.15	North
59	Zucchis	–61.39	–50.59	64.45	4.81	64.44	0.07	South
60	Cabeus	–85.51	–41.21	100.03	4.20	99.53	0.04	South
61	Ibn Bajja	–86.31	–75.02	12.40	1.56	12.38	0.13	South
62	Ganswindt	–79.81	111.32	76.80	3.92	76.75	0.05	South
63	Doerfel	–68.94	–108.46	68.79	3.39	68.77	0.05	South
64	Klaproth A	–68.21	–21.87	29.80	2.41	29.82	0.08	South
65	Newton A	–79.98	–20.77	64.16	3.63	64.16	0.06	South
66	Helmholtz D	–66.36	54.10	45.00	4.63	44.97	0.10	South
67	Wexler V	–67.98	84.19	21.80	2.82	21.78	0.13	South
68	Boussingault N	–71.37	61.19	15.30	2.43	15.24	0.16	South
69	Crommelin C	–65.45	–143.99	42.80	2.66	42.77	0.06	South
70	Abbe M	–61.76	175.25	29.00	2.77	28.99	0.10	South
71	Berlage R	–64.11	–167.50	27.50	1.89	27.65	0.07	South
72	Boussingault T	–63.03	43.05	19.10	2.95	19.09	0.15	South
73	Helmholtz A	–64.51	51.56	16.60	2.23	16.59	0.13	South
74	Wiechert E	–83.57	176.04	18.40	2.82	18.41	0.15	South
75	Pentland	–64.61	11.39	57.97	3.15	57.98	0.05	South
76	Cysatus	–66.23	–6.35	47.90	4.20	47.88	0.09	South
77	Rutherfurd	–61.16	–12.22	47.50	4.13	47.50	0.09	South
78	Blancanus	–63.64	–21.89	111.19	4.82	111.20	0.04	South
79	Kinau	–60.76	14.92	41.60	2.17	41.58	0.05	South
80	Mutus	–63.66	29.99	77.53	3.85	77.50	0.05	South
81	Manzinus	–67.45	26.42	98.84	4.82	98.82	0.05	South
82	Moretus	–70.64	–6.02	114.54	6.12	114.51	0.05	South
83	Curtius	–67.04	4.18	95.97	3.99	95.95	0.04	South
84	Simpelius	–72.57	14.67	70.02	4.98	70.02	0.07	South
85	Schomberger	–76.64	24.93	82.77	5.65	82.76	0.07	South
86	Amundsen	–84.57	83.10	103.42	5.65	103.44	0.05	South
87	Kuhn	–84.47	–152.63	17.50	1.46	17.50	0.08	South
88	Shoemaker	–88.11	48.12	51.80	3.81	51.81	0.07	South
89	Svedberg	–81.68	65.12	15.00	3.07	15.01	0.20	South
90	Wapowski	–83.07	53.88	12.00	2.64	12.00	0.22	South
91	Boguslawsky	–72.82	43.06	97.43	4.02	97.41	0.04	South
92	Gill	–63.73	75.88	64.13	3.73	64.15	0.06	South
93	Wexler	–68.88	90.73	50.40	3.73	50.40	0.07	South
94	Rittenhouse	–74.28	107.10	25.40	3.15	25.38	0.12	South
95	Hale	–74.13	92.06	84.19	4.79	84.17	0.06	South
96	Cysatus A	–64.32	–0.81	13.60	2.75	13.59	0.20	South
97	Curtius A	–68.47	2.62	12.20	2.44	12.19	0.20	South
98	Bailly U	–71.24	–76.01	23.30	1.82	23.28	0.08	South
99	Newton E	–79.86	–37.43	17.00	2.96	17.02	0.17	South
100	Lambert	25.78	–20.97	30.30	2.66	30.28	0.09	Equator
101	Timocharis	26.71	–13.10	34.00	3.18	33.96	0.09	Equator
102	Autolycus	30.70	1.50	39.30	3.74	39.31	0.10	Equator
103	Bessel	21.74	17.94	15.80	1.78	15.82	0.11	Equator
104	Vitruvis	17.66	31.31	30.90	1.98	30.91	0.06	Equator
105	Clerke	21.68	29.81	7.00	1.47	7.02	0.21	Equator
106	Plinius	15.34	23.59	43.40	3.04	43.38	0.07	Equator
107	Cajal	12.60	31.09	9.00	1.79	9.03	0.20	Equator
108	Carrel	10.68	26.66	15.80	2.09	15.77	0.13	Equator
109	Sinas	8.85	31.60	12.10	2.26	12.13	0.19	Equator

Table 1 — *Continued.*

Sr. No.	Crater Name	Average Latitude	Average Longitude	LROC Diameter (D) (km)	LROC Depth (d) (km)	Calculated Diameter (D) (km)	d/D	Pole
110	Ross	11.69	21.72	24.80	2.36	24.81	0.10	Equator
111	Arago	6.18	21.42	25.90	2.39	25.92	0.09	Equator
112	Sosigenes	8.70	17.61	17.40	1.71	17.36	0.10	Equator
113	Manners	4.58	20.01	15.00	1.90	15.02	0.13	Equator
114	Aristrllus	33.87	1.20	55.54	3.82	55.57	0.07	Equator
115	Lalande	–4.45	–8.62	24.00	2.65	24.03	0.11	Equator
116	Agrippa	4.07	10.48	45.50	3.24	45.49	0.07	Equator
117	Godin	1.82	10.14	35.20	3.40	35.21	0.10	Equator
118	Cayley	3.94	15.10	14.20	3.12	14.18	0.22	Equator
119	Delambre	–1.92	17.40	51.63	3.41	51.65	0.07	Equator
120	Lansberg	–0.29	–26.62	40.20	3.01	40.22	0.07	Equator
121	Turner	–1.41	–13.25	12.00	2.62	12.01	0.22	Equator
122	Pytheas	20.56	–20.59	20.30	2.46	20.28	0.12	Equator
123	Eratosthenes	14.46	–11.29	58.36	3.60	58.38	0.06	Equator
124	Triesnecker	4.18	3.61	25.90	2.74	25.88	0.11	Equator
125	Chladni	3.99	1.13	13.50	2.61	13.51	0.19	Equator
126	Horrocks	–4.00	5.87	29.90	2.81	29.89	0.09	Equator
127	Muller	–7.64	2.09	19.70	2.10	19.67	0.11	Equator
128	Thebit	–22.00	–4.03	55.90	3.36	55.84	0.06	Equator
129	Nicollet	–21.95	–12.49	15.20	1.93	15.22	0.13	Equator
130	Konig	–24.23	–24.67	23.60	2.50	23.64	0.11	Equator
131	Moltke	–0.59	24.19	6.50	1.33	6.47	0.20	Equator
132	Seeliger	–2.22	3.01	8.80	1.90	8.77	0.22	Equator
133	Mosting	–0.71	–5.89	25.40	2.65	25.39	0.10	Equator
134	Euclides	–7.41	–29.56	12.20	2.55	12.20	0.21	Equator
135	Norman	–11.79	–30.36	10.30	2.01	10.31	0.20	Equator
136	Darneye	–14.62	–23.56	15.40	2.96	15.39	0.19	Equator
137	Werner	–28.02	3.27	71.65	4.63	71.64	0.06	Equator
138	Fermat	–22.71	19.80	37.60	2.58	37.61	0.07	Equator
139	Maskelyne	2.14	30.07	24.20	2.57	24.20	0.11	Equator
140	De-Morgan	3.31	14.90	10.20	1.87	10.19	0.18	Equator
141	Ukert	7.72	1.38	22.30	3.17	22.31	0.14	Equator
142	Bessarlon	14.85	–37.31	10.40	2.18	10.38	0.21	Equator
143	Draper	17.56	–21.74	8.80	1.76	8.80	0.20	Equator
144	Macro Polo A	14.90	–1.96	7.00	2.92	7.00	0.42	Equator
145	Milichius A	9.25	–32.06	9.00	1.63	9.01	0.18	Equator
146	Aratus	23.56	4.53	10.60	1.86	10.63	0.18	Equator
147	Conon	21.67	1.99	21.20	3.05	21.22	0.14	Equator
148	Bode A	8.99	–1.17	12.40	2.72	12.39	0.22	Equator
149	Hortensius	6.45	–28.00	14.50	2.95	14.53	0.20	Equator
150	Lansberg D	–3.02	–30.63	11.00	2.21	11.01	0.20	Equator
152	Madler	–11.23	29.77	27.60	2.83	29.89	0.10	Equator
153	Sinas E	9.66	31.04	9.00	1.62	9.00	0.18	Equator
154	Gambart C	3.32	–11.80	12.40	2.27	12.38	0.18	Equator
155	Ammonius	–8.53	–0.82	8.90	1.96	8.90	0.22	Equator
156	Hipparchus J	–7.59	3.21	14.00	2.24	14.00	0.16	Equator
157	Dionysius	2.77	17.31	17.40	2.91	17.39	0.17	Equator
158	Bruce	1.16	0.38	6.80	1.25	6.80	0.18	Equator
159	Mac Millan	24.19	–7.83	7.40	0.46	7.39	0.06	Equator
160	Huxley	20.20	–4.53	4.40	0.55	4.41	0.13	Equator
161	Blagg	1.22	1.46	5.40	0.91	5.41	0.17	Equator
162	Schwarzschild L	69.11	121.77	46.40	2.10	46.45	0.05	North
163	Pythagoras D	64.51	–72.33	29.10	1.58	29.12	0.05	North
164	Gioja	83.34	1.76	42.70	1.20	42.68	0.03	North

Table 1 — *Continued.*

Sr. No.	Crater Name	Average Latitude	Average Longitude	LROC Diameter (D) (km)	LROC Depth (d) (km)	Calculated Diameter (D) (km)	d/D	Pole
165	Challis	79.56	8.98	57.45	1.67	57.43	0.03	North
166	Epigenes	67.50	–4.63	54.41	2.40	54.40	0.04	North
167	Bosch	86.82	134.04	19.80	1.18	19.77	0.06	North
168	Nansen C	83.41	55.51	34.40	1.67	34.38	0.05	North
169	Thiessen W	75.82	–172.91	22.30	0.24	22.29	0.01	North
170	Gamow Y	67.71	143.29	28.80	1.16	28.81	0.04	North
171	Nother U	67.20	–123.69	36.50	3.72	36.49	0.10	North
172	Poinsot P	76.65	–149.86	28.30	1.64	28.27	0.06	North
173	Plaskett S	81.00	150.48	17.10	3.40	17.12	0.20	North
174	Plaskett U	82.42	162.22	15.50	3.04	15.47	0.20	North
175	Petermann A	74.84	87.63	18.00	3.47	18.01	0.19	North
176	Petermann C	71.53	57.31	13.30	3.02	13.32	0.23	North
177	Emden F	62.99	–171.13	19.20	3.80	19.21	0.20	North
178	Kirkwood T	68.99	–165.27	18.60	4.43	18.60	0.24	North
179	Nansen U	81.54	82.60	15.20	3.50	15.22	0.23	North
180	Mouchez M	80.26	–50.17	17.60	3.31	17.58	0.19	North
181	Main L	81.45	22.64	14.40	3.06	14.37	0.21	North
182	Strabo L	64.19	53.48	26.20	3.26	26.21	0.12	North
183	Goldschmidt D	75.40	–7.75	14.20	3.33	14.20	0.23	North
184	Epigenes A	67.04	–0.43	17.30	3.05	17.29	0.18	North
185	Idel son	–81.28	112.96	59.78	2.83	59.74	0.05	South
186	Neumayer M	–71.72	80.33	32.90	4.32	32.89	0.13	South
187	Le Gentil A	–74.64	–52.61	32.80	3.58	32.83	0.11	South
188	Zhamg Yuzhe	–69.06	–137.86	38.40	1.89	38.39	0.05	South
189	Schomberger A	–78.59	23.57	31.10	3.79	31.20	0.12	South
190	Grotrian	–66.15	128.25	37.30	4.04	37.28	0.11	South
191	Shackleton	–89.54	133.37	20.40	4.15	20.38	0.20	South
192	Schrodinger J	–78.36	155.39	15.30	3.44	15.29	0.22	South
193	Casatus C	–72.25	–30.28	17.40	3.27	17.40	0.19	South
194	Bailly G	–65.63	–59.44	18.70	3.79	18.71	0.20	South
195	Schomberger G	–77.02	7.38	17.20	3.26	17.19	0.19	South
196	Hale Q	–76.50	83.88	24.20	4.14	24.18	0.17	South
197	Wilson F	–70.48	–39.60	14.00	3.10	13.97	0.22	South
198	Lyman P	–67.08	158.53	13.70	3.26	13.73	0.24	South
199	Schrodinger B	–68.06	141.40	24.60	3.46	24.60	0.14	South
200	Mutus L	–61.86	24.84	19.20	3.31	19.21	0.17	South
201	Bailly F	–67.48	–69.56	17.20	3.35	17.18	0.19	South
202	Maclear	10.52	20.10	20.10	0.74	20.09	0.04	Equator
203	Thean Senior	–0.83	15.42	18.00	3.42	18.02	0.19	Equator
204	Sabine	1.38	20.06	30.20	1.40	30.00	0.05	Equator
205	Ritter	1.98	19.18	19.60	1.31	29.61	0.07	Equator
206	Gambart	0.93	–15.23	25.70	1.13	25.67	0.04	Equator
207	Lassell	–15.51	–7.91	23.00	0.85	23.02	0.04	Equator
208	Birt	–22.37	–8.59	16.40	3.66	16.41	0.22	Equator
209	Kunowsky	0.02	–32.52	18.40	0.83	18.38	0.05	Equator
210	Lubiniezky	–17.89	–23.92	43.60	0.65	43.59	0.01	Equator
211	T. Mayer	15.54	–29.16	33.60	1.95	33.58	0.06	Equator
212	Polybias A	–23.05	27.99	16.80	4.09	16.80	0.24	Equator
213	Hell A	–33.92	–8.45	20.90	1.03	20.89	0.05	Equator
214	Rhaeticus A	1.72	5.19	10.70	1.03	10.72	0.10	Equator

Notes: The craters labeled from 1 to 161 follow the general mechanism and those from 162 to 214 obey a different mechanism.

Table 2 Observations for unknown Craters

Sr. No.	Crater Name	Average Latitude	Average Longitude	LROC Diameter (D) (km)	LROC Depth (d) (km)	Calculated Diameter (D) (km)	d/D	Pole
1	Crater 9	83.87	–56.92	9.00	1.25	9.00	0.14	North
2	Crater 14	81.68	–23.73	10.00	1.83	10.01	0.18	North
3	Crater 15	85.66	–26.01	7.80	1.55	7.79	0.20	North
4	Crater 16	80.29	66.08	7.00	1.32	7.00	0.19	North
5	Crater 20	80.79	53.85	7.00	1.26	6.98	0.18	North
6	Crater 21	77.00	35.16	7.70	1.07	7.71	0.14	North
7	Crater 23	79.26	28.51	5.80	1.07	5.80	0.18	North
8	Crater 24	80.26	22.72	9.60	1.53	9.62	0.16	North
9	Crater 25	81.36	19.01	5.70	1.11	5.68	0.19	North
10	Crater 26	82.25	11.63	7.20	1.11	7.20	0.15	North
11	Crater 27	63.90	13.58	8.80	1.83	8.78	0.21	North
12	Crater 28	68.39	10.75	4.90	0.88	4.89	0.18	North
13	Crater 29	68.81	16.87	3.40	0.27	3.39	0.08	North
14	Crater 30	65.50	54.23	7.50	1.26	7.49	0.17	North
15	Crater 31	87.12	–33.59	6.60	0.99	6.60	0.15	North
16	Crater 32	87.00	–36.71	6.30	0.93	6.30	0.15	North
17	Crater 33	87.43	–35.17	2.70	0.41	2.69	0.15	North
18	Crater 34	87.53	–29.04	3.80	0.63	3.81	0.16	North
19	Crater 35	87.67	–40.03	2.20	0.38	2.20	0.17	North
20	Crater 36	88.25	–11.56	3.60	0.45	3.60	0.12	North
21	Crater 37	88.26	25.74	7.40	1.19	7.39	0.16	North
22	Crater 38	87.94	30.31	5.90	0.89	5.91	0.15	North
23	Crater 39	87.30	67.72	11.60	1.73	11.59	0.15	North
24	Crater 40	87.19	58.57	6.60	1.09	6.60	0.17	North
25	Crater 41	86.64	58.68	5.00	0.95	5.01	0.19	North
26	Crater 43	84.63	31.59	3.70	0.63	3.69	0.17	North
27	Crater 44	77.70	101.76	11.70	1.69	11.69	0.14	North
28	Crater 45	78.89	100.42	11.80	1.12	11.79	0.10	North
29	Crater 46	79.02	99.06	5.70	1.05	5.70	0.18	North
30	Crater 49	79.55	55.47	16.80	2.12	16.78	0.13	North
31	Crater 50	72.78	101.32	13.00	2.37	13.01	0.18	North
32	Crater 10	–79.88	–138.98	9.00	1.79	9.00	0.20	South
33	Crater 11	–69.60	–41.18	7.00	1.33	6.98	0.19	South
34	Crater 17	–81.01	–8.50	8.40	1.64	8.38	0.20	South
35	Crater 18	–81.43	19.73	7.70	1.19	7.69	0.15	South
36	Crater 20	–83.28	9.27	9.00	1.81	8.99	0.20	South
37	Crater 21	–72.64	50.79	8.00	1.18	8.01	0.15	South
38	Crater 22	–62.52	3.61	4.30	0.75	4.29	0.17	South
39	Crater 25	–84.06	–8.50	9.80	1.45	9.79	0.15	South
40	Crater 27	–71.35	176.69	7.50	1.18	7.51	0.16	South
41	Crater 31	–69.47	72.75	6.50	1.24	6.49	0.19	South
42	Crater 35	–67.78	72.04	7.50	1.42	7.49	0.19	South
43	Crater 36	–67.45	70.72	5.70	1.19	5.70	0.21	South
44	Crater 38	–64.53	95.91	5.40	0.89	5.38	0.16	South
45	Crater 39	–63.04	97.56	18.30	1.42	18.29	0.08	South
46	Crater 40	–64.59	101.38	8.40	1.41	8.38	0.17	South
47	Crater 41	–68.94	102.18	7.40	1.07	7.40	0.14	South
48	Crater 42	–67.69	104.45	9.80	1.40	9.80	0.14	South
49	Crater 44	–69.27	111.23	7.20	1.47	7.19	0.20	South
50	Crater 45	–70.68	113.71	10.60	2.14	10.58	0.20	South
51	Crater 46	–63.64	145.70	9.60	1.32	9.59	0.14	South
52	Crater 47	–63.46	148.15	8.80	1.44	8.80	0.16	South
53	Crater 48	–60.62	149.03	18.90	2.82	18.88	0.15	South
54	Crater 50	–62.23	136.57	9.60	1.75	9.59	0.18	South
55	Crater 1	–2.99	–7.36	4.40	0.72	4.10	0.16	Equator
56	Crater 2	–3.68	–7.59	3.80	0.24	3.78	0.06	Equator

Table 2 — *Continued.*

Sr. No.	Crater Name	Average Latitude	Average Longitude	LROC Diameter (D) (km)	LROC Depth (d) (km)	Calculated Diameter (D) (km)	d/D	Pole
57	Crater 3	–3.17	–9.54	2.80	0.19	2.80	0.07	Equator
58	Crater 4	–3.31	–9.77	2.90	0.18	2.91	0.06	Equator
59	Crater 5	–4.19	–9.93	2.60	0.31	2.58	0.12	Equator
60	Crater 6	–9.6	–5.04	4.20	0.68	4.18	0.16	Equator
61	Crater 7	–9.84	–7.56	3.20	0.59	3.21	0.18	Equator
62	Crater 8	–10.3	–7.37	3.40	0.28	3.42	0.08	Equator
63	Crater 9	–10.73	–5.78	3.70	0.53	3.71	0.14	Equator
64	Crater 10	–11.28	–5.22	4.80	0.50	4.80	0.10	Equator
65	Crater 11	–10.9	–3.15	3.10	0.32	3.12	0.10	Equator
66	Crater 12	–10.64	–2.82	2.80	0.25	2.81	0.09	Equator
67	Crater 13	–10.73	–2.71	3.20	0.15	3.20	0.05	Equator
68	Crater 14	–16.25	6.75	3.60	0.37	3.65	0.10	Equator
69	Crater 15	–29.16	–5.04	4.40	0.80	4.42	0.18	Equator
70	Crater 16	–0.91	7.87	2.90	0.33	2.88	0.11	Equator
71	Crater 17	1.26	7.01	4.20	0.52	4.22	0.12	Equator
72	Crater 18	–8.64	30.32	3.80	0.67	3.80	0.18	Equator
73	Crater 19	–6.64	11.64	3.20	0.32	3.19	0.10	Equator
74	Crater 20	–7.97	13.84	3.00	0.29	3.02	0.10	Equator
75	Crater 21	–15.01	19	4.50	0.68	4.48	0.15	Equator
76	Crater 22	–21.94	10.54	4.70	0.70	4.71	0.15	Equator
77	Crater 23	–28.59	1.44	3.80	0.49	3.80	0.13	Equator
78	Crater 24	0.41	–14.51	2.60	0.35	2.58	0.14	Equator
79	Crater 25	0.29	1.96	2.40	0.33	2.41	0.14	Equator
80	Crater 3	71.99	–156.28	20.20	1.91	20.18	0.09	North
81	Crater 4	64.68	–125.46	35.40	1.81	35.38	0.05	North
82	Crater 5	71.69	–131.52	14.80	2.88	14.78	0.19	North
83	Crater 6	77.30	–102.62	23.70	2.40	23.72	0.10	North
84	Crater 7	81.40	74.91	28.00	2.56	28.00	0.09	North
85	Crater 8	70.93	85.06	29.50	3.29	29.48	0.11	North
86	Crater 10	72.93	–82.19	23.60	2.64	23.58	0.11	North
87	Crater 11	82.82	–46.80	21.90	1.14	21.90	0.05	North
88	Crater 13	83.79	–13.83	12.60	1.97	12.59	0.16	North
89	Crater 17	81.44	56.68	10.00	0.92	9.98	0.09	North
90	Crater 18	82.10	54.12	2.00	0.92	1.99	0.46	North
91	Crater 19	80.61	57.57	24.00	1.36	24.00	0.06	North
92	Crater 39	87.30	67.72	11.60	1.73	11.59	0.15	North
93	Crater 44	77.70	101.76	11.70	1.69	11.69	0.14	North
94	Crater 45	78.89	100.42	11.80	1.12	11.79	0.10	North
95	Crater 49	79.55	55.47	16.80	2.12	16.78	0.13	North
96	Crater 50	87.23	101.32	13.00	2.37	13.01	0.18	North
97	crater 1	64.38	172.52	17.40	3.32	17.42	0.19	North
98	crater 2	66.37	175.61	15.80	3.87	15.77	0.24	North
99	Crater 12	83.14	–68.62	16.80	3.91	16.80	0.23	North
100	Crater 1	–74.31	20.09	37.90	3.73	38.01	0.10	South
101	Crater 2	–70.06	–48.39	19.00	3.00	19.00	0.16	South
102	Crater 3	–73.06	–45.8	35.60	2.72	35.58	0.08	South
103	Crater 4	–75.99	–32.96	33.00	1.07	33.02	0.03	South
104	Crater 5	–80.04	31	22.20	2.95	22.17	0.13	South
105	Crater 6	–87.43	–109.5	13.40	1.73	13.37	0.13	South
106	Crater 7	–70.18	–100.31	33.40	1.91	33.39	0.06	South
107	Crater 9	–70.15	–100.37	33.00	2.14	33.02	0.06	South
108	Crater 12	–79.49	–40.19	11.00	2.30	10.99	0.21	South
109	Crater 14	–78.37	–29.17	17.30	0.38	17.30	0.02	South
110	Crater 15	–80.54	–0.75	11.50	1.17	11.50	0.10	South

Table 2 — *Continued.*

Sr. No.	Crater Name	Average Latitude	Average Longitude	LROC Diameter (D) (km)	LROC Depth (d) (km)	Calculated Diameter (D) (km)	d/D	Pole
111	Crater 16	–80.61	–8.55	12.20	1.74	12.21	0.14	South
112	Crater 23	–77.14	11.27	13.40	2.53	13.38	0.19	South
113	Crater 24	–84.26	–13.05	11.60	1.16	11.58	0.10	South
114	Crater 26	–71.32	162.4	11.60	2.51	11.60	0.22	South
115	Crater 28	–65.45	–158.82	22.90	0.89	22.91	0.04	South
116	Crater 29	–63.39	–153.8	23.40	2.25	23.39	0.10	South
117	Crater 30	–62.3	–155.72	13.20	2.72	13.20	0.21	South
118	Crater 33	–69.72	71.15	11.30	1.20	11.29	0.11	South
119	Crater 34	–68.69	71.44	8.70	0.84	8.68	0.10	South
120	Crater 39	–63.04	97.56	18.30	1.42	18.29	0.08	South
121	Crater 45	–70.68	113.71	10.60	2.14	10.58	0.20	South
122	Crater 48	–60.62	149.03	18.90	2.82	18.88	0.15	South
123	Crater 13	–76.00	–53.40	16.90	3.22	16.89	0.19	South
124	Crater 19	–82.27	11.60	30.80	3.87	30.81	0.13	South
125	Crater 8	–62.45	–104.47	23.40	3.62	23.41	0.15	South

Notes: This table has 125 unknown craters. Craters labeled from 1 to 78 follow the general mechanism and those from 79 to 125 obey a different mechanism.

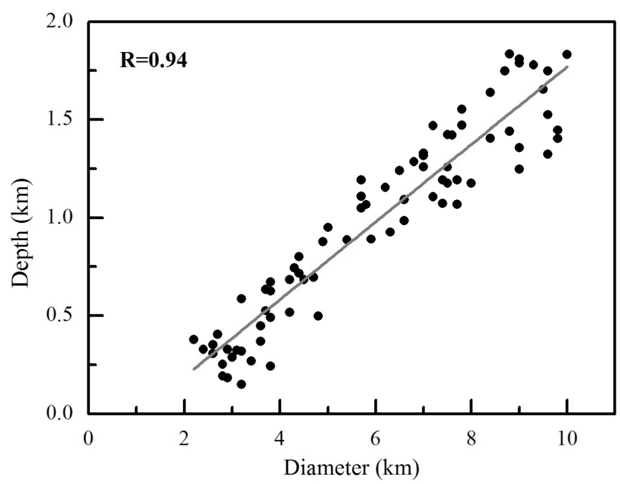

Fig. 6 The depth d of the craters is plotted as a function of diameter D. The correlation between d and D is $\sim$0.94.

between depth (d) and diameter (D) of the 78 craters, which has a correlation coefficient of $r\sim$0.94. Thus we may further conjecture the formation mechanism of these craters is similar to what we suggested in the known craters category (cf. Fig. 3), following the scaling-law of linearity. The histogram of these 78 craters is shown in Figure 7, and exhibits an unambiguous increase in depth with increasing diameter, thereby following the formation mechanism described earlier regarding known craters that obey the linearity law.

However, 47 unknown craters also do not follow the $d - D$ linearity law as may be noted from Figure 8. Thus we may interpret their formation mechanisms as being similar to those craters included in Figure 5.

4.3 Latitude and Longitude Distribution

Craters are mostly created by the impact of asteroids comprised of various materials, mostly of iron, nickel and other metals (Atkinson 2015). Feldspathic craters are composed of olivine, glass, etc. (Mustard et al. 2011). However, as mentioned earlier, the presence of water molecules depends on the location of the crater on the Moon. Thus we have analyzed the latitude and longitude distribution of physical properties of all 339 craters considered for investigation in the current paper. We measured latitude, longitude as well as d and D for each crater. Shown in Figure 9 is the d/D ratio as a function of latitude for the craters. This figure reveals that craters

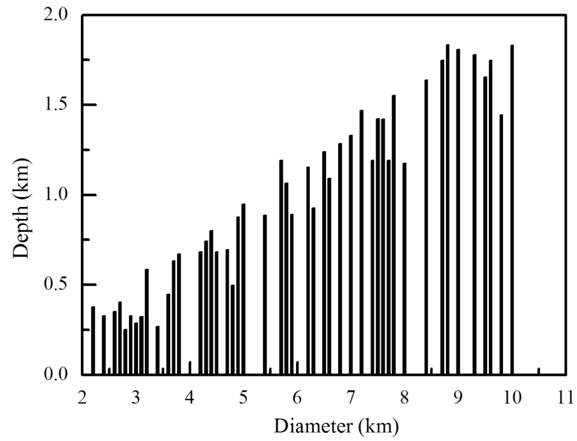

Fig. 7 Histogram of unknown craters following the linearity law.

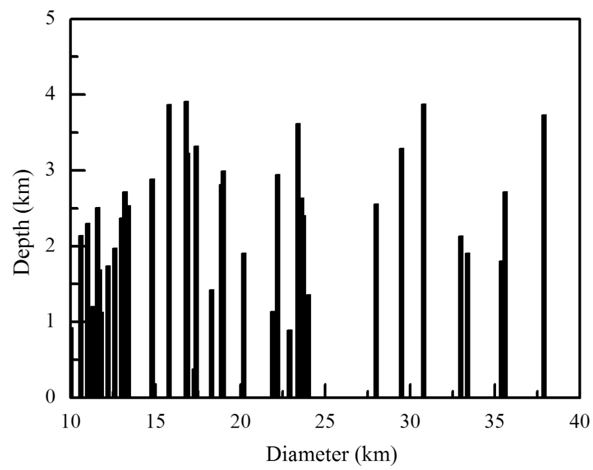

Fig. 8 Histogram of unknown craters which do not follow the linearity law.

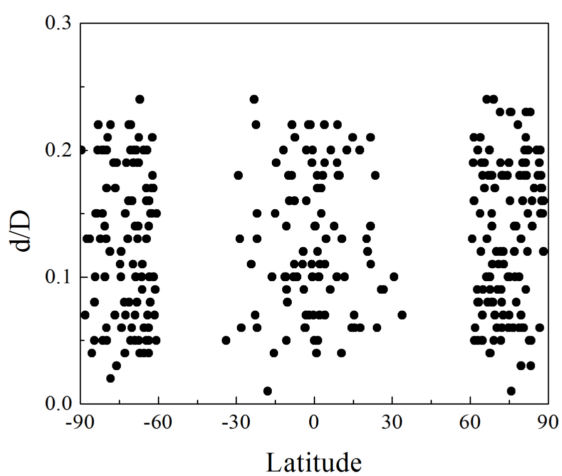

Fig. 9 The d/D ratio as a function of latitude for all craters under current investigation.

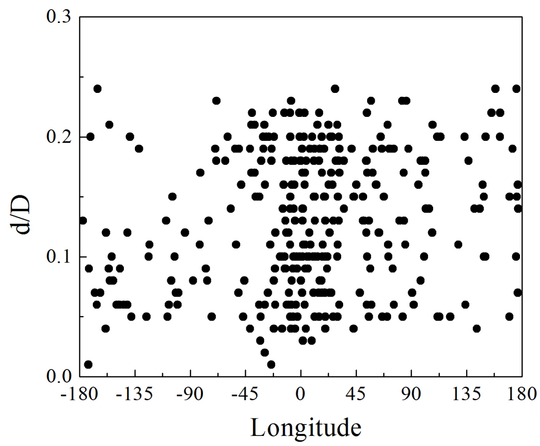

Fig. 10 The d/D ratio as a function of longitude for all craters under current investigation.

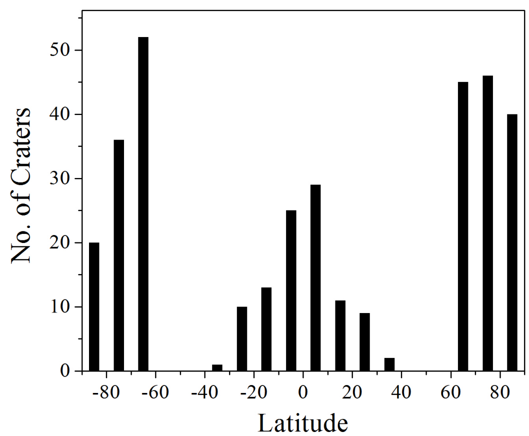

Fig. 11 Number of craters as a function of latitude. The latitudes are divided into 100 bins in view of resolution limit and crater size.

are mostly concentrated near the equatorial ($-30°$ to $+30°$) zone and high latitude ($-60°$ to $-90°$ and $+60°$ to $+90°$) zone in both hemispheres. The craters with the d/D ratio ranging from 0.01 to 0.24 exist in these three dominant latitude zones on the Moon. By contrast, craters with small to large size are found to exist in all longitudes as shown in Figure 10, however, with a larger concentration near the equator ($\pm30°$).

The number density of craters observed in each of the 100 bins representing latitude and longitude is shown in Figures 11 and 12 respectively. Craters found between $-30°$ and $+30°$ are considered to be located near the equatorial region. A total of 97 craters are found in this zone near the equator. The highest number of craters (131) is found to be in the North Pole region ($+60°$ to $+90°$). We identify 108 craters located in the South Pole region ($-60°$ to $-90°$). This suggests that the Moon is highly cratered in the high latitude North and South Pole regions. By contrast, longitude distribution is dominated by the near equatorial region as revealed from Figure 12. A total of 150 craters exist in this zone near the equator, while in the eastern ($+30°$ to $+180°$) and western ($-30°$ to $-180°$) regions, 111 and 78 craters are found respectively.

5 DISCUSSION AND CONCLUSIONS

In this investigation, we study a total of 339 lunar craters comprised of known and unknown craters in the context to their physical properties such as depth, diameter, lon-

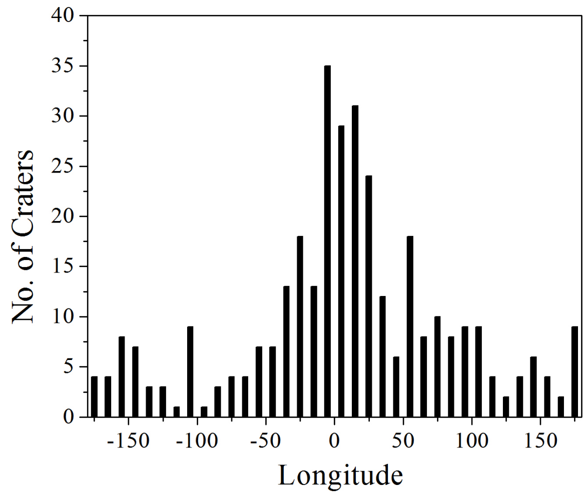

Fig. 12 Number of craters as a function of longitude. The longitudes are divided into 100 bins in view of resolution limit and crater size.

gitude and latitude distribution, etc. The measurements of depth and diameter of the craters are done employing LROC data. We also calculate the diameter employing our formula which revealed the results with an accuracy of $\geq 98\%$ compared to what was obtained from the LROC website. We discover that in both known and unknown categories there are craters which follow the d/D linearity scaling law as well as those which do not follow the scaling law. We propose that there are different formation mechanisms for these two classes of craters.

Out of 224 known craters, 161 craters show linearity between depth (d) and diameter (D) with correlation coefficient $R \sim 0.84$. The remaining 53 known craters do not follow the linearity between d and D. Similarly, out of 125 unknown craters, 78 craters follow the linearity relation between d and D with a correlation coefficient $r \sim 0.94$, but the remaining 47 craters do not follow it. We propose that there are different mechanisms for formation of craters following the linearity between d and D and those that do not follow it. The craters following the d/D linearity law might have been formed by asteroids/impactors with a proportional area and having heavy materials. Thus, we may conclude that the craters whose depth and diameter are large must have been formed by asteroids with large diameter that were dominated by high density metal. The second class of craters (not following the d/D linearity law) might have been formed by either enriched heavy metal asteroids with smaller diameters or low density material (e.g. silicon) having larger diameter. We may further conclude that the craters whose diameter is small and depth is more were formed by canonically shaped asteroids having high density metals.

Our study also reveals dominant zones of craters in latitude as well as in longitude. According to the latitude distribution, we found a total of 108 craters near the South Pole and 131 craters near the North Pole ($\pm 60°$ to $90°$ zones). A total of 97 craters were found in the equatorial zone. On the other hand, longitude distribution reveals 150 craters in the equatorial zone ($-30°$ to $+30°$ zone), while in the eastern ($+30°$ to $+180°$) and western ($-30°$ to $-180°$) regions there are 111 and 78 craters respectively.

Acknowledgements We sincerely acknowledge the data and other software help received from the LROC website. We express sincere gratitude to Prof. Mark Robinson, at the School of Earth and Space Exploration, ASU, Tempe, AZ, USA, for extremely useful suggestions to complete this research work. We are also grateful to Mr. Vallabhbhai M. Patel, President, Kadi Sarva Vishwavidyalaya, for providing us all necessary help for the present investigation. We say thank you to Dr. Arun K. Awasthi, Visiting Research Fellow at USTC, Hefei, China for reviewing the paper and Ms. Veena Choithani, research scholar in our group, for help in preparing figures and plots. Authors also acknowledge Dr. Neeraj Srivastava at the Physical Research Laboratory, Ahmedabad for providing guidance in data analysis.

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