The Lunar rayed-crater population — Characteristics of the spatial distribution and ray retention

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A B S T R A C T

The global statistics for young impact craters on the Moon is used to unravel potential spatial asymmetries, that may have been introduced by the particular orbital configuration of a synchronously rotating satellite. Only craters that exhibit bright ejecta rays extending for several crater radii were considered in this study. This crater population is younger than about 750 Ma. The shape of the crater size-frequency distribution does not show strong dependence on the target properties (mare vs. highlands). However, slightly lower frequencies indicate a shorter retention of the visibility of rays in mare units when their visibility is purely due to immaturity and not due to composition. Rays of small craters fade away much faster. Large, old, rayed craters sustain their visibility longer than the average crater population because of the compositional contrast between rays and mare material, and thus obscure the cratering record when investigated for spatial variations. Using the existence of rays purely based on optical maturity instead of visibility as marker horizon for the Copernican–Eratosthenian boundary, suggests a shift from 1.1 Ga to 750 Ma.

The spatial distribution of lunar rayed craters, namely the latitudinal and longitudinal frequency variations, does not agree with previous analytical and numerical studies. Although there is an apparent hemispherical asymmetry centred close to the apex, the density distribution is patchy and no predicted spatial pattern could be confirmed. Spatial distribution corrections accounting for the lower frequencies in the mare areas did not result in a better agreement with the analytical estimates. Density variations are less than 15% over vast parts of the lunar surface, and the uncertainties for absolute surface ages are similar. However, variations of up to 50% are found even for the more numerous small craters. These extreme values are located at high latitudes. A combination of crater-forming projectile flux distribution and micrometeorite bombardment, which acts on maturation of the ray systems, could prove as an explanation for the contradicting observed rayed crater distribution. An analysis of the older craters is more challenging (on the Moon) because earlier geological processes complicate the setting, and the orbital configuration of the Moon–Earth–Sun–projectile system altered with time.

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1. Introduction

Impact crater formation is one of the most common geological processes on the rocky bodies of the solar system and crater counts can be used to determine relative and absolute surface ages. If the crater-production rate and size-frequency distribution are known (e.g., Shoemaker et al., 1963; Hartmann, 1966; Oberbeck et al., 1977; Neukum, 1983; Ivanov, 2001). This approach assumes a random and globally uniform crater–production rate, implying an isotropic velocity distribution for the projectile population or a target body massive enough to deviate the projectiles. The orbital configuration and synchronous rotation of almost all planetary satellites suggest, however, that a satellite’s surface may exhibit spatial variations of the crater-production rate. A latitudinal dependence might be found because the inclination distribution of the projectile candidates dominantly scatters around the equatorial plane (Halliday, 1964; Le Feuvre and Wieczorek, 2006, 2008; Gallant et al., 2009). A longitudinal dependence results from synchronous rotation and the relative velocity between satellite and projectile. This suggests preferential impact cratering on the leading side of the satellite (Wiesel, 1971; Wood, 1973; Shoemaker and Wolfe, 1982; Horedt and Neukum, 1984; Zahhle et al., 1998, 2001, 2003; Morota and Furumoto, 2003; Morota et al., 2005, 2008; Gallant et al., 2009). If the majority of projectiles approach the planet–satellite system with inclination close to the satellite’s orbit plane, the planet could act as a gravitational lens depending on the distance between planet and satellite, causing an asymmetry between nearside and farside of the satellite. Projectiles would be focused onto the nearside of the satellite (Turski, 1962; Wiesel, 1971; Bandermann and Singer, 1973; Wood, 1973; Le Feuvre and
Scattered all over the Moon, the rayed craters constitute a group of craters that are easily recognized and least affected by other geological processes. This crater group therefore allows us to study the spatial distribution of craters on the Moon for the period in which the orbital configuration, Earth–Moon distance, and the nearside–farside situation has been similar to today's situation.

Although the formation process of crater ejecta rays is not fully understood, rays are described as filamentous, high-albedo deposits that are radial or sub-radial to fresh craters and often extend many crater radii from the parent crater (Hawke et al., 2004). Their visibility depends mainly on the state of optical maturity of the ray material; if the composition of the ray deposits differs from the surrounding terrain, they can remain visible longer, particularly in the mare units (Hawke et al., 2004). The presence of crater rays is considered as the marker to define the Copernican–Eratosthenian boundary, and the persistence of non-compositional rays has been estimated to last less than about 1.1 Ga (Wilhelms, 1987).

2. Crater size–frequency distribution: Age, ray retention and the role of composition

To describe the spatial and size–frequency distribution of the lunar rayed crater population we analysed the Clementine 750 nm image mosaic data on a map scale of 1:3 million, although the image data, having a nominal pixel resolution of 100 m/pixel would allow for a larger scale. Crater detection at sizes down to about 1 km in diameter is considered complete. The image data were searched for craters which exhibit rayed ejecta extending multiple crater radii with higher albedo than the surroundings. The detection of rayed craters was done by eye based on the albedo map and constrained by mineral-ratio data presented as a RGB composite image mosaic with band ratios 750 nm/415 nm shown in red (R), 750 nm/950 nm in green (G) and 415 nm/750 nm in blue (B), so that the crater ejecta rays of young craters appear in bright blue (Pieters et al., 1994). Positively identified craters were marked by their centre points and scaled by their crater diameters in a GIS system for latitudes between 70°N and 70°S. The polar regions beyond these limits were excluded from the analysis to avoid biasing due to low illumination and phase-angle changes at higher latitudes. Fig. 1 shows the crater size–frequency distribution scaled by their diameters.

A total of 1615 craters were registered with craters as small as 500 m in diameter, but only craters with diameters greater or equal to 1 km (1263 craters, out of which 273 craters are larger than 5 km in diameter) are considered here to be detected without misses. Thus, our observed diameter range extends to considerably smaller crater diameters than in earlier measurements. Previous studies focussed on the lunar farside and were restricted to crater diameters larger than 10 km or 5 km (e.g. McEwen et al., 1997; Morota and Furumoto, 2003). Others (Grier et al., 2001) investigated craters globally, but considered only craters with diameters larger than 20 km. The detection rate of rayed craters at comparable sizes in this work is about 15% lower than earlier observations and measurements (McEwen et al., 1997; Morota and Furumoto, 2003). This corresponds roughly to the uncertainties stated by McEwen et al. (1997). None of...
the craters which McEwen et al. (1997) listed as old or questionable were considered in this study. Therefore, the set of rayed craters considered here, is a significant subset of the young craters discussed by McEwen et al. (1997), Grier et al. (2001) or Morota and Furumoto (2003). However, this study does not intend to represent all the craters of the Copernican Epoch as listed by Wilhelms et al. (1978) and discussed by McEwen et al. (1997), but to focus on a crater population that is as homogenous as possible. The cumulative crater size-frequency distribution found in this study is given in Fig. 2.

2.1. Age of the population and ray retention

Our age analysis is based on the standard procedure of cratering age determination with technical details described by the Crater Analysis Techniques Working Group (1979). Crater retention ages are derived by fitting a crater-production function (time-invariant crater size-frequency distribution) to the observed crater distribution. Linked to a certain reference diameter $D$ ($\geq 1$ km), the cumulative crater frequency, $N_{\text{cum}}(D)$ is translated to absolute age through a cratering chronology function (describing the change in cratering rate through time). Fig. 2 shows the crater size-frequency distribution of the rayed-crater population in comparison with isochrones for 750 Ma, 1.1 Ga and 2 Ga average surface age, calculated using the crater-production function given by Ivanov (2001) and the cratering chronology function from Neukum et al. (2001).

Applied to the rayed-crater population, the crater retention age for a given segment of the rayed-crater distribution is equal to the typical retention time of rays. Hence, fitted isochrones indicate (the lower limit of) the absolute ray retention time for rays. Hawke et al. (2004) grouped lunar rays into compositional and immaturity rays, of which the latter will naturally disappear with time. Compositional rays will only disappear when the ray material is fully diluted by the surrounding material, for example due to vertical mixing or lateral transport of material from adjacent units. These processes of mixing and dilution of compositional rays take much longer than the maturation process (e.g., Pieters et al., 1985; Blewett and Hawke, 2001). The visibility of rays (their albedo contrast) in the 750 nm maturation process (e.g., Pieters et al., 1985; Blewett and Hawke, 2004) and discussed by McEwen et al. (1997), but to focus on a crater population that is as homogenous as possible. The cumulative crater size-frequency distribution found in this study is given in Fig. 2.

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The crater size-frequency distribution for the area outside the mare units are fitted by an isochrone for an average surface age of 750 Ma (following Ivanov, 2001; Neukum et al., 2001) down to a crater diameter of about 5 km, although slight deviations are observed (Fig. 4). The crater frequency drops below the isochrone at a diameter around 20 km, similar to observations of McEwen et al. (1997). We can assign this deviation to the transition between simple and complex craters, which is at about 21 km diameter for the highlands (Pike, 1981). The highland crater population seems to exceed the isochrone for crater diameters around 10 km in diameter before the curve continues well below the isochrones (for craters of 5 km and smaller in diameter) because of the crater size-dependence of ray maturity (Grier et al., 2001; Hawke et al., 2004). The steepening above the isochrone was already described by McEwen et al. (1997), but is found for the rayed-crater population not to be as pronounced as earlier crater counts suggest (Fig. 4). The crater distribution measured by McEwen et al. (1997) is in general steeper in comparison to isochrones and to the pure rayed-crater population described here.

The mare crater size-frequency distribution appears to be somewhat different from the highland one. For the larger crater size range (larger than 50 km in diameter), craters inside mare units are more abundant compared to the 750-Ma isochrone. The large-crater excess is attributable to the prolonged ray visibility when caused by composition rather than immaturity. In Fig. 5, the mare crater size-frequency distribution for the entire rayed-crater population is plotted and compared to the distribution of the crater population without those for which the ray visibility is due to composition rather than immaturity. Whereas the larger crater population inside mare units appears to exceed the 750-Ma isochrone, it fits well to this isochrone after the compositional rayed craters were removed from the population (following Grier et al., 2001). Extracting large craters from the population results in an increase of the gradient representing the cumulative distribution (compare the discussion on resurfacing treatment by Werner, 2009), and therefore the correlation between observation and isochrone improves. Generally, the distribution at intermediate crater diameters (5 km to 12 km) is better represented by a 650-Ma isochrone (following Ivanov, 2001; Neukum et al., 2001), implying either a comparatively lower crater-production rate for the mare units or more rapid decay in the visibility of rays. The latter is
The geological difference between mare and highland units does not significantly influence the shape of the crater size-frequency distribution, although a slight tendency towards lower numbers is observed for the mare units compared to highland units. The global distribution of rayed craters will be used to investigate spatial asymmetries for the cratering rate on the lunar surface representative for at least the last 750 Ma. The ratio of crater frequencies outside and inside mare units is determined and used to correct the crater numbers in the spatial investigations to avoid biases, especially at the smaller-size range.

The GIS system provides tools to select craters with distance from (for example) the apex or antapex with dependence on size or any other attribute assigned to the crater, such as latitude, longitude or diameter. Consequently, any rayed-crater subset can be defined and compared to the predicted crater-rate asymmetries suggested or discussed by Turskii (1962), Halliday (1964), Wiesel (1971), Bandermann and Singer (1973), Wood (1973), Shoemaker and Wolfe (1982), Horedt and Neukum (1984), Zahnle et al. (1998, 2001, 2003), Morota and Furumoto (2003), Morota et al. (2005, 2008), Le Feuvre and Wieczorek (2005, 2006, 2008), Gallant et al. (2009).

In the previous sections we showed that the frequency of craters in mare units is lower than in highland units, and a satisfactory explanation for this difference is yet not found. Possible explanations include global asymmetry of the crater distribution on Moon, or simply the lower detectability of the rays in the mare units. If the latter is the main reason, the global analysis of spatial distribution will be inaccurate. To account for this, we calculate the ratio of the crater frequencies within and outside mare units (Fig. 6). The ratio shows that the small (~5 km in diameter) craters appear in highland units 1.85 times more often than in the mare units. Thus, if we assume that the low detectability of the craters is the reason for lower frequency of the craters in mare units, we have to adjust the numbers of the craters by the ratio of 1.85 in mare areas. The crater range 5–50 km gives an average ratio of frequencies of 1.45. This variance between mare and highland crater size-frequency distribution is evaluated (Fig. 6) and corrected to avoid any bias due to detectability in the spatial investigation.

3. Spatial crater distribution — Detectable asymmetries?

The ray detectability is lower in mare units than on highland units, and therefore the population observable in the mare units is depleted. The apparently younger mare crater population reflects compositional differences. Following Noble et al. (2007), the term space weathering summarizes the micrometeorite bombardment and the interaction of solar wind and cosmic rays (energetic charged particles) with the surface of atmosphere-less bodies, such as the Moon. It changes the optical properties of the surface so that with time the brightness of the surface decreases while the spectral reddening increases. The process is faster for mare units than highland areas. A possible explanation is that the contrast between fresh and matured soils is already lower (albedo ranges between 7% and 10%) compared to highland soils (albedo ranges between 11% and 18%) and that the process of maturation is accelerated due to the relative iron content, one of the significant compositional differences (Morris, 1976; Allen et al., 1996; Noble et al., 2001).

3.1. Latitudinal dependence

The study of the latitudinal dependence aims to explore whether the spatial crater distribution is affected by projectiles mainly moving close to the ecliptic plane. As suggested by Halliday (1964), Le Feuvre and Wieczorek (2006, 2008), Gallant et al. (2009), higher crater frequencies may be expected closer to the equator than to the pole. To test this model prediction, craters were extracted from the database according to latitude using a 30° sized moving-window at steps of 3°. This was done for diameter ranges of 1 to 5 km and 5 to 50 km. The total population behaves similarly to the crater population with diameters between 1 km and 5 km. Consequently, any rayed-crater subset can be defined and compared to the predicted crater-rate asymmetries suggested or discussed by Turskii (1962), Halliday (1964), Wiesel (1971), Bandermann and Singer (1973), Wood (1973), Shoemaker and Wolfe (1982), Horedt and Neukum (1984), Zahnle et al. (1998, 2001, 2003), Morota and Furumoto (2003), Morota et al. (2005, 2008), Le Feuvre and Wieczorek (2005, 2006, 2008), Gallant et al. (2009).

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without corrections for mare units. The crater frequencies are normalized according to the average and plotted against latitude, and error bars are shown for the uncorrected crater frequencies. The statistical uncertainties for the corrected crater population are slightly smaller.

In comparing the observed and the predicted normalized density distribution (e.g., Le Feuvre and Wieczorek, 2008), we find the observed deviations to be larger and more random. No clear density pattern is observed for craters with diameters larger than five kilometres. At latitudes around 20°N the frequency drops. This is only marginally related to the lower numbers found in the mare regions, because it remains even after the corrections for lower frequencies in the mare units. The frequency variations for the smaller craters show a trend which is opposite to the one predicted by Le Feuvre and Wieczorek (2008). High crater frequencies are found at high latitudes. The correction for effects of the mare units (dashed line in Fig. 7A) does not change this tendency although a minor reduction of the amplitude of the variations is observed.

3.2. Longitudinal dependence

The leading hemisphere of synchronously rotating satellites is expected to be cratered at a higher rate than on the trailing hemisphere (e.g., Shoemaker and Wolfe, 1982; Horedt and Neukum, 1984; Zahnle et al., 1998). This asymmetry results because the orbital velocity of the satellite is large compared to the space velocity of the impactor. The cratering rate asymmetry of the Moon is hence much smaller. In comparing the observed and the predicted normalized density distribution (e.g., Le Feuvre and Wieczorek, 2008), we find the observed deviations to be larger and more random. No clear density pattern is observed for craters with diameters larger than five kilometres. At latitudes around 20°N the frequency drops. This is only marginally related to the lower numbers found in the mare regions, because it remains even after the corrections for lower frequencies in the mare units. The frequency variations for the smaller craters show a trend which is opposite to the one predicted by Le Feuvre and Wieczorek (2008). High crater frequencies are found at high latitudes. The correction for effects of the mare units (dashed line in Fig. 7A) does not change this tendency although a minor reduction of the amplitude of the variations is observed.

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**Legend:**
- Red: $D=1–5$ km, av. freq. $=27.8 \times 10^{-6}\text{km}^{-1}$
- Red dashed: $D=1–5$ km, av. freq. $=31.8 \times 10^{-6}\text{km}^{-1}$, mare corr. = 1.85
- Gray: $D=5–50$ km, av. freq. $=7.7 \times 10^{-6}\text{km}^{-1}$
- Gray dashed: $D=5–50$ km, av. freq. $=8.4 \times 10^{-6}\text{km}^{-1}$, mare corr. = 1.45
- Analytical prediction (LeFouvre & Wieczorek, pers. com.)
search radius of 30°, the pattern differs significantly. All map derivatives show a more patchy distribution, although corrected for the mare units the density maximum is found rather at high latitudes than near the equator. A dominance at the leading side is still observed, but the apex and its surroundings show relatively lower densities.

3.3. Nearside–farside dependence

Whether there is a visible effect between the nearside and the farside, is debated for the Moon (Turski, 1962; Wiesel, 1971; Bandermann and Singer, 1973; Wood, 1973; Le Feuvre and Wieczorek, 2005; Gallant et al., 2009). This effect most likely acts at smaller separations between planet and satellite if the majority of projectiles approach the system with inclination close to the satellite-orbit plane. Fig. 7C shows the observed crater population in comparison with the analytically predicted one. The strongest influence between nearside and farside is the differing composition affecting the detectability of rayed craters. However, the observed population is representative only for very recent impact bombardment so that any emphasizing of a nearside–farside effect due to smaller separation distance would not be detected.

4. Discussion and conclusions

Our study of the spatial and size-frequency distribution of rayed craters on the Moon show that spatial asymmetries exist. They do not,
however, show patterns predicted by models that use the present day orbital configuration of the Moon. The patterns are more complex. Density variations are less than 15% for most of the lunar surface, and the uncertainties for absolute surface ages are similar. However, variations of up to 50% are found even for small and numerous craters. These extreme values are located at high latitudes. Although geological

Fig. 10. Comparison of the analytically predicted spatial crater distribution (A, after LeFeuvre and Wieczorek, pers.com.), the observed total crater distribution (Fig. 9), which is corrected for lower frequencies in the mare units (B) and uncorrected (C) and an impression of the surface composition (D) as given through mineral-ratio data presented as a RGB composite image mosaic with band ratios 750 nm/415 nm shown in red (R), 750 nm/950 nm in green (G) and 415 nm/750 nm in blue (B), (Pieters et al., 1994).
processes forming the lunar surface do not affect the rayed-crater distribution, the inherited target properties of earlier geological activity or even primordial crustal compositional differences have a strong influence on the ray retention (Fig. 10). We show that the number of small craters exhibiting rayed ejecta in mare units is almost two times lower than in the highland units. A likely explanation for the difference is the accelerated ray obliteration in mare areas because of the higher iron content and lower albedo contrast. This is true only for so-called maturity rays, which fade away due to space weathering, but not if the rays are visible due to compositional differences. Large, old, rayed craters sustain their visibility longer than the average crater population because of compositional contrast between rays and mare material, and thus obscure the cratering record when investigated for spatial variations as predicted from analytical and numerical studies.

The observed spatial crater distribution, which contradicts the predicted crater distribution and shows highest frequencies at the poles instead of near the equator, is puzzling, as there are no obvious compositional variations (Fig. 10) and a recent reorientation of the lunar surface with respect to the spin axis is unlikely (e.g. Wisdom, 2006). However, it could be a result of the predicted cratering rate distribution: a combination of the crater-forming projectile flux and the micrometeorite bombardment. The latter acts on the maturation horizon for the Copernican

... system, refer to Table 6 of the manuscript. This work was supported by the Norwegian Research Council through a Centre of Excellence grant to PGP.


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