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Characteristics of small young lunar impact craters focusing on current production and degradation on the Moon

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ABSTRACT

Analysing the size-frequency distribution of very small lunar craters (sized below 100 m including ones below 10 m) using LROC images, spatial density and related age estimations were calculated for mare and terra terrains. Altogether 1.55 km^2 area was surveyed composed of 0.1–0.2 km^2 units, counting 2784 craters. The maximal areal density was present at the 4–8 m diameter range at every analysed terrain suggesting the bombardment is areally relatively homogeneous.

Analysing the similarities and differences between various areas, the mare terrains look about two times older than the terra terrains using <100 m diameter craters. The calculated ages ranged between 13 and 20 Ma for mare, 4–6 Ma for terra terrains. Substantial fluctuation (min: 936 craters/km^2, max: 2495 craters/km^2) was observed without obvious source of nearby secondaries or fresh ejecta blanket produced fresh crater. Randomness analysis and visual inspection also suggested no secondary craters or ejecta blanket from fresh impact could contribute substantially in the observed heterogeneity of the areal distribution of small craters – thus distant secondaries or even other, poorly known resurfacing processes should be considered in the future. The difference between the terra/mare ages might come only partly from the easier identification of small craters on smooth mare terrains, as the differences were observed for larger (30–60 m diameter) craters too. Difference in the target hardness could more contribute in this effect.

It was possible to separate two groups of small craters based on their appearance: a rimmed thus less eroded, and a rimless thus more eroded one. As the separate usage of different morphology groups of craters for age estimation at the same area is not justifiable, this was used only for comparison. The SFD curves of these two groups showed characteristic differences: the steepness of the fresh craters' SFD curves are similar to each other and were larger than the isochrones. The eroded craters' SFD curves also resemble to each other, which are less steep than the isochrones. These observations confirm the expectation that as the time passes by, rims are erased and depressions became shallower, presenting such observations for the first time in this small crater size range.

1. Introduction

The lunar surface provides an ideal, large area to record and analyse cratering rate at the near Earth region because of the lack of atmosphere, substantial weathering and also large scale tectonic and volcanic events (Ivanov 2001, Neukum et al., 2001; Orgel et al., 2017). The recent impact rate in the near Earth space is an important information that might influence actions/preparations for mitigation against bombarding bodies on the Earth, including mitigation models for any possible permanent lunar base. From scientific point of view regarding the Moon, the exact knowledge of the current impact rate influences strongly the recent age estimation results and helps to understand the regolith turnover rate. The morphological and thermophysical characteristics of young craters also provide information on the properties of regolith and on the realization of the impact process itself. Huge dataset is available on the lunar surface by recent missions, especially by SELENE (Haruyama et al., 2008) and LRO (Robinson et al., 2010) imaging campaigns, but a large part of this recently produced data has not been exploited yet, thus it is worth to analyse it, partly to clarify the recent impact rate of the Moon.

This work **aims** a small step toward the usage of small lunar craters in age and impact bombardment rate estimation in the near Earth region with pointing to some important characteristics of spatial density, morphology and degradation of small and young craters. It is still not straightforward, how the smallest observable lunar craters are relevant for age estimation mainly because of the unknown role of secondary craters, and as they erode faster than larger ones, thus possibly require specific handling. The evaluation of small craters (100 m diameter and below) is a difficult task, because of the above listed issues. As the dataset of lunar images is pretty large and exact, and the understanding of near Earth meteoroid impact bombardment rate is a current aim, thus it is important to understand how to use the small craters on the lunar surface for impact rate and related age estimation. Recent data form the Lunar Reconnaissance Orbiter improved substantially our understanding on the lunar surface and geological history (Braden et al., 2014; Greenhagen

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et al., 2010; Wilson and Head, 2017) and provides perfect information to understand cratering rate.

In this work we focus on the following **three main questions**: 1. How the degradation of small and young lunar craters could be followed by the images to identify their related characteristics? 2. How much the regional setting (mainly terra/mare regolith differences) influence the smallest crater's occurrence, morphology and possibility for identification? 3. What kind of observational difficulties exist in counting the smallest lunar craters? The new contribution of this work to the field are: analysis of new images, separate analysis of rimmed and rimless crater groups (where the first group of craters look more fresh and the second more eroded in appearance). The comparison of images at different lunar surface types also provides new data on any possible terrain type related differences in crater morphology or observability, and some new methodological findings that could be used in future works on small lunar impact craters' analysis. According to these aims this work is not to calculate exact ages using small lunar craters, however several age values are indicated here but mainly as approaches to see the differences and identify the possible problems with calculating ages using small craters.

1.1. Overview of earlier results

The morphology of lunar craters have been used since the beginning of space era to understand crater formation methods (Melosh, 1989; Cintala and Grieve, 1989) and morphological variability (Gault et al., 1975; Schultz, 1976). New high resolution data with global coverage from LRO (Scholten et al., 2012; Jolliff et al., 2011; Waters et al., 2010) revolutionized our view on the Moon and supported the improvement of several scientific topics, including the timing of volcanism with localized recent activity at Ina caldera (Braden et al., 2014), global chronology of mare basalts' related activity (Hiesinger et al., 2000) and the understanding of various crater related processes (Jozwiak et al., 2012) including the behaviour of impact melts (Bray et al., 2010).

Earlier works in **lunar cratering rate analysis** used different production functions. The Neukum production function analyses crater density first between 300 km and 10 m (Neukum, 1983), and in the later upgraded version between 100 km and 10 m (Neukum et al., 2001) to provide model ages. Recent attempts aimed to apply the crater statistics for small sized (>100 m) craters too (Banks et al., 2012; Braden et al., 2014; Watters et al., 2012) - however recent degradation might happen (Mahanti et al., 2016) and influence the age results, and helps in the better understanding of cratering rate (Hartmann, 1970; Neukum et al., 2001). Several works searched for and identified recent lunar craters that formed between the acquisition of images of the same area at different periods (Daubar et al., 2011) including the comparison with relatively older Apollo-era images (Oberst et al., 2012), while in some cases the impact flashes were also observed from the Earth by the recently formed fresh crater (Madeido et al., 2014; Robinson et al., 2015; Speyerer et al., 2016).

Several critical points and existing questions are summarized below. Characteristic differences were observed between the crater density of melt ponds and their surroundings, while its explanation is not straightforward, especially because of the differences between the nearby ejecta and melt ponds might be related to different erasing processes (Zanetti et al., 2015) or target properties or even different arrival periods of secondary ejecta and even later arriving melt sheets by slow flow. Melt ponds on the Moon were compared to their surroundings and the results suggested that different target properties might influence the produced SFD of small craters (van der Bogert et al., 2010), thus impact melt deposits could provide substantially younger age values as smaller craters form on higher than weaker density targets (van der Bogert et al., 2015) – however this effect might support the characterization of the target material. The target hardness dependence of small craters' SFD was also identified on Mars, comparing the cratering statistics of rafted plates and the areas separating them at Elysium Planitia (Dundas et al., 2010). The SFD of small craters is also more sensitive to any alteration that could be more frequent because of small size to erasure (Williams et al., 2017) and knowledge on geological context should support the interpretation. The analysis of relatively small areas (<1 km^2) might provide larger uncertainties than size of error bars (van der Bogert et al., 2015). Analysis of mainly four large craters' ejecta (Copernicus, Tycho, North Ray, and Cone craters) supported that the bombardment rate was almost constant in the last 3 Ga (Neukum et al., 2001), and recently these rates were improved further (Hiesinger et al., 2012) using new data.

There is an ongoing **debate on the possible usage of small (<100 m dimeter) craters** in planetary surface age estimation according to the size-frequency distribution (SFD) analysis (Shoemaker et al., 1963), mainly because of the unclarified role of secondary craters. Since the early work of Moore et al. (1980) several papers have been published on the potential usage of small lunar craters for chorology, some of them argue that the smallest crater fraction could be used for age estimation (Williams et al., 2014), while others argue against (McEwen et al., 2005a, 2005b; McEwen and Bierhaus, 2006), however based on the original estimation of Hartmann (2005, 2007) the isochrones are relevant for all craters together, e.g. primaries and secondaries counting together. It is worth mentioning that the handling of nearby secondaries (where the secondary craters show increased spatial density toward the young and relatively larger primary, from where ejected the blocks produced the secondaries) is easier. For example in the case of Tycho and Aristarchus the population of secondary candidates change radially, possibly connected to the differences in arriving periods of various ejecta units or secondaries forming blocks (Krishna and Kumar 2016). The handling and taking into account of distant secondaries is a greater problem (Robinson et al., 2015) – the estimation of the consequences from them on age estimation is an unresolved issue.

Different approaches and argumentations were used to handle this problem. Based on **fireball occurrence** form the Earth it was possible to reproduce lunar and Martian crater-count chronometry system (Williams et al., 2014), and the related analysis suggests that the cratering rate could be constant in the last roughly 100 million year or more. McEwen et al. (2005a, 2005b) suggests that the **steepening of SFD power law slope** could come from secondaries. Analysing LRO and SELENE lunar images together Hiesinger et al. (2012) discussed the discrepancy between impact melts and ejecta regarding the occurrence of craters on them, finding usually good agreement with radiometric and exposure ages of the Apollo 16, 17, and 12 landing sites, and consistency with a constant impact rate over the last 3 Ga – but small variations of the impact rate cannot be excluded. On Mars secondary candidates were also found to produced steep SFD shapes in certain cases (McEwen et al., 2005a, 2005b; Preblich et al., 2007; Calef et al., 2009; Werner et al., 2009; Watters et al., 2016).

Analysing the small craters' distribution on the young surface of **Europa** satellite of Jupiter, characteristic difference was observed regarding the shapes of craters where the secondaries' tend toward smaller depth/diameter ratio, and among them adjacent secondaries showed stronger this tendency than distant ones (Bierhaus and Schenk, 2010). Adjacent secondaries could be well identified there because of low "background noise" from the young surface, however these were larger secondaries than the size class this work analysis, and no treatment for the identification of the distant secondaries was found. Based on the work of Bierhaus et al. (2005) around 95% of craters below 1 km diameter, which partly could be identified by their spatial arrangement showed clustering occasionally at even hundred km from the primary, and their occurrence could be partly estimated by statistical approach. Based on such estimations around 50% of spatially random craters could be secondaries.

In the case of **craters on Mars**, small distant secondaries were identified by McEwen (2003) around the 10 km diameter Zunil crater. Based on the observation of recent craters and fading rate for Mars, the production rate was estimated to be around $10^{-8} – 10^{-6}$ crater/m^2/year recently for craters with diameter between 25 and 100 m (Malin et al., 2006). Similar estimations from other authors range between 10^{-7}–10^{-9}