Icarus 314 (2018) 327–344

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

The mixing of lunar regolith: Vital updates to a canonical model

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ARTICLE INFO

Keywords:
Moon
Surface
Regoliths
Impact processes
Cratering

ABSTRACT

In this work we update the regolith mixing model presented by Gault et al. (1974), including new input values and reworking key parameters. Much as Gault et al. did, we present a way to calculate the rate at which lunar regolith is overturned at depth. The model describes a mixing front that proceeds downward from the surface following a power-law function of time. Our most important update is the inclusion of secondary impacts. Our calculations show that secondaries are necessary to produce the reworking rate inferred from the depth distribution of surface-correlated material in Apollo cores (Fruchter et al., 1977; Morris, 1978; Blanford, 1980), from the rate at which splotches rework the top 3 cm of regolith (Speyerer et al., 2016), and from the rate at which Diviner cold spots (Bandfield et al., 2014) and crater rays (Pieters et al., 1985; Hawke et al., 2004; Werner and Medvedev, 2010) are reworked into background regolith. Overturn calculations that only consider the impact of primaries fail to describe observed reworking rates at all depths and timescales. We conclude that secondary impacts dominate mixing in the top meter of lunar regolith.

1. Introduction

Each time an object impacts a planetary body, material is excavated from depth and deposited in the proximity as an ejecta deposit. Impacting objects can be micron-sized grains of cosmic dust, kilometer-sized asteroids, or any of all twelve orders of magnitude in between. The size distribution of objects that strike the Moon is largely stochastic, governed by mutual impacts and the power laws of pulverization (Strom et al., 2005, 2015). Impacting objects generate craters correlated to the impactor size, velocity, and material properties of the impactor and target (e.g. Holsapple and Schmidt, 1980; Holsapple and Schmidt, 1982; Schmidt and Housen, 1987; Holsapple, 1993). The power-law size distribution of impactors and the well-constrained relationship between impactor size and crater size allow statistical modeling of regolith evolution, including impact gardening.

Impact gardening is the process by which impacts redistribute regolith material, removing grains from depth and re-depositing them near the surface. Gardening is also called ‘mixing’ or ‘overturn’ (e.g. Gault et al., 1974; Arnold, 1975) because it muddles the otherwise distinct stratigraphic arrangement of materials with depth by repeatedly and stochastically inverting the depth-distribution of materials. Explorations of the impact-driven evolution of regolith have continued to provide insight into the depth profiles of cosmic ray tracks, volatile elements, abundance of cosmogenic radionuclides, percentages of different lithologic components, and grain size distributions (e.g. Fruchter et al., 1976; Fruchter et al., 1977; Morris, 1978; Blanford, 1980; Crider and Vondrak, 2003; Vondrak and Crider, 2003; Heiken et al., 1991; Hurley et al., 2012). Each study contributes to our understanding of the process and consequences of impact gardening and its wider influence on lunar stratigraphy, the lifetime of rays and other surface features such density and albedo anomalies, and the burial, exposure, and break down of volatiles and rocks.

Gault et al. (1974) presented a pioneering regolith mixing model predicated on the assumption that impact flux is a probabilistic process that obeys the Poisson distribution (Gault et al., 1972; 1974). In Gault et al. (1974), regolith overturn is defined to occur when a point at depth has been influenced by an impact event. Their model mathematically describes the frequency with which material at that depth is affected by an impact, and transported from depth to the near surface. The success rate of overturning events is presented by Gault et al. as a function of core input parameters: time, impact flux, and crater scaling. These parameters, together with a statistical method based on Poisson law and the stochastic impact flux describe the rate and probability of overturn at depth as a function of time.

The Gault et al. (1974) model has had significant and ongoing influence on the development of regolith evolution models (Arnold, 1975;

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https://doi.org/10.1016/j.icarus.2018.05.023
Received 7 October 2017; Received in revised form 21 May 2018; Accepted 25 May 2018

Spencer, 1987; Harmon et al., 2001; Schorghofer et al., 2016; Hirabayashi et al., 2017; Huang et al., 2017) and analyses of the reworking depth of surface exposure effects in Apollo cores (Morris, 1978; Blanford, 1980). However, key parameters such as impact flux and the relationship between meteorite properties and crater size have not been updated since the 1974 study. Building on the legacy of the Gault et al. (1974) model, we present a refreshed approach to the overturn of lunar regolith, in which we explicitly rework and update the key parameters originally included in the model: crater scaling and the flux of crater-forming impactors.

Finally, and most importantly, we include the regolith overturn effects of secondary impacts. Gault et al. (1974) noted the inclusion of secondaries as an important future addition to the model; in this study we follow through on that suggestion. Since 1974, our understanding of the intensity of secondary cratering has evolved, with scale and effect revealed by recent studies of impact ejecta (e.g. Vickery, 1986; Vickery, 1987; Cintala and McBride, 1995) and observations of martian (McEwen et al., 2005; Preblich et al., 2007) and lunar craters (Allen, 1979; Bart and Melosh, 2007; Robinson et al., 2015; Speyerer et al., 2016). Largely due to the inclusion of secondaries, we calculate a rate of mixing that is much higher than that predicted by Gault et al. (1974) at all depths and timescales. The high secondary-driven reworking rate is in better agreement with several validating cases, including the depth-density profile of surface maturity indicators and the rate at which surface features with well-constrained depth and longevity such as rays and cold spots (Bandfield et al., 2014) are mixed into the background. The scale of the improvement suggests that secondaries play a compelling role in the evolution of lunar regolith.

2. Model

The Gault et al. (1974) model and the work we present here are predicated on the assumption that overturn follows a Poisson probability distribution with time that is functionally dependent on the flux of meteoritic impacts and the size of the craters that those impacts produce. The key components of the model are 1) a Poisson expression that describes the theoretical success-rate of a point at depth being inside the excavated volume of a crater over a time interval and 2) a crater production function that describes the cumulative number of craters of a certain diameter that form per unit area per unit time. The Poisson expression shown here is effectively unaltered from that put forth by Gault et al. (1974). We present a review of it here for clarity. We then describe an updated and more explicit treatment of crater scaling and geometry and refresh crater efficiency input parameters based on observations and experiments conducted since 1974.

2.1. The Poisson expression

The probability function for the Poisson distribution describes the probability of observing n events over an interval:

$$P_d(n;\lambda) = \frac{\exp(-\lambda)(\lambda)^n}{n!} \quad \text{for} \quad n = 0, 1, 2... \tag{1}$$

The cumulative probability function describes the probability that at least n events have occurred and takes the form:

$$P_c(n;\lambda) = \sum_{i=1}^{n} \frac{\exp(-\lambda)(\lambda)^i}{i!} = 1 - P_d(n) \tag{2}$$

Using Eq. (2), one can compute the probability that at least n events will occur if the average number of events per interval is some value λ. Tables of λ values have been calculated numerically for situations where n successful events occur at 10, 50, and 99% probability. A table in Molina (1942) documents numerically derived values for λ for the range $0 \le n \le 153$. Gault et al. (1974) numerically derived values for λ in the range $153 \le n \le 10^6$, with order of magnitude steps in between. Values for λ at 10, 50, and 99% probability that are used to calculate overturn in this work can be found in Appendix Table 1.

Table 1

Values for the average number of events per interval. Values where $1 < n < 100$ are from Molina (1942). Values where $n > 100$ are from Table 1 in Gault et al. (1974).

Values used in this manuscript			
λ : the average number of events per interval from the Cumulative Poisson Distribution			
n : the cumulative number of events	Percent Probability		
	10%	50%	99%
1	0.105	0.693	4.605
2	0.530	1.678	6.638
3	1.102	2.674	8.406
4	1.742	3.672	10.05
6	3.150	5.670	13.11
8	4.655	7.670	16.00
10	6.221	9.670	18.87
20	14.53	19.67	31.85
30	23.33	29.67	44.19
40	32.11	39.67	56.16
10^2	87.42	99.67	1.247×10^2
3×10^2	2.780×10^2	2.997×10^2	3.418×10^2
10^3	9.596×10^2	9.997×10^2	1.075×10^3
3×10^3	2.930×10^3	3.000×10^3	3.129×10^3
10^4	9.872×10^3	1.000×10^4	1.023×10^4
3×10^4	2.978×10^4	3.000×10^4	3.041×10^4
10^5	9.959×10^4	1.000×10^5	1.007×10^5
3×10^5	2.993×10^5	3.000×10^5	3.013×10^5
10^6	9.9687×10^5	1.000×10^6	1.002×10^6

In the following section, we present the geometric derivation of the Poisson expression used by Gault et al. (1974) to describe the number of times a point at depth is successfully overturned by a crater-forming impact per unit area and unit time on the Moon and include important steps and reasoning.

To begin, we imagine a simplistic geometric vision of some planetary surface where all possible points of impact exist in a round-edged square (Fig. 1). There is some point Q on the round edged square surface and some point U directly below (Fig. 2). By considering the probability the sub-surface point U within the simple geometric scheme will or will not be disturbed by an impact event, we can present overturn as a function of the Poisson-derived average number of events, λ, and time, t.

Let us geometrically define the planetary surface. An overturn-able point Q exists somewhere inside or on the boundary of a square with side s and area, $A_{Square} = s^2$. The square is surrounded by a rounded square band such that $A_{Band} = 4rs + \pi r^2$. To illustrate the purpose of the band, imagine point Q is directly on one corner of the square (see the star in Fig. 1). The rounded band describes the additional area inside which a crater of radius r could form and still influence some point within the square. When we consider a planetary surface, the square model surface (A_{Square}) is much larger than the radius of any crater; thus, the band will effectively disappear. For now, it allows some useful geometric manipulation. $A_{Surface}$ describes the geometry of the total planetary surface area:

$$A_{Surface} = A_{Square} + A_{Band} \tag{3}$$

$$= s^2 + 4rs + \pi r^2 \tag{4}$$

In order for an impact event with effective excavation radius r to excavate Q, the epicenter of impact must be within a circle of radius r and area, $A_\circ = \pi r^2$. Any object that strikes within $A_\bigcirc$ with excavation radius r **will** excavate point Q. Any circular crater whose epicenter of impact is within the square, along the boundary of the square, in the band, or on the boundary of the band **could** excavate point Q. The