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Crater-ray formation by impact-induced ejecta particles

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ABSTRACT

We performed impact experiments with granular targets to reveal the formation process of crater "rays", the non-uniform ejecta distributions around some fresh craters on the Moon and planets. We found mesh patterns, loosely woven with spaces like a net, as ejecta. A characteristic length of spaces between meshes was evaluated, and an angle, defined as the ratio of the characteristic length to the distance from the ejection point, was obtained as ∼a few degrees. These features are similar to the results of the analyses of the ray patterns around two lunar craters, Glushko and Kepler. Numerical simulations of granular material showed that clear mesh pattern appeared at lower coefficients of restitution between particles but was less clear at larger one, suggesting that the inelastic collisions between particles cause the clear mesh-pattern formation of impact ejecta.

1. Introduction

Around many craters on the solid surfaces of celestial bodies such as the Moon, "rays", which extend from craters in sub-radially to radially oriented filaments and diffuse patches (Melosh, 1989), are observed (Fig. 1). The nature of rays has been studied long before the first spacecraft missions to the Moon, and the understanding of the lunar rays has been furthered by high-resolution images taken by recent lunar and planetary spacecraft. On the brightness of the rays, Hawke et al. (2004) summarized that lunar rays are bright due to the compositional contrast with the surrounding terrain (e.g., ray material containing highlands-rich primary ejecta and the adjacent dark mare surface) and/or the presence of immature (fresh, high-albedo) material. Various models on the formation process of such contrast have been proposed such as the emplacement of primary ejecta, the deposition of local material from secondary craters, high-speed debris ejected from the spall zone, and surface scouring by ejecta (e.g., Oberbeck, 1971; Allen, 1977; Schultz and Gault, 1985; Melosh, 1989; Hawke et al., 2004). However, another remarkable feature of crater rays, the spatial non-uniformity, seems to have not been much discussed; the number of studies on the generation mechanism of the non-uniformities of rays is relatively small (e.g., Andrews (1977) found the ray formation in explosion cratering experiments, where spatial patterns may correlate with the non-uniformities of high-velocity detonation products, and Shuvalov (2012) recently numerically simulated the ray formation process based on the interaction of shock waves with old craters, where the ray pattern should relate with the non-uniformities of existing craters).

The purpose of this paper is to provide an alternative model on the generation mechanism of the spatial non-uniformities of crater rays. We focus on the granular materials such as regolith and small fragments caused by impact as ejecta. Granular materials that begin in initially uniform density with some velocity distribution dissipate their initial kinetic energy through the inelastic collisions between granular particles. In the field of physics, it has been shown that inelastically colliding particles spontaneously form "clusters", locally overdense (the high degrees of the concentration of particles) regions, and that the density of the granular system becomes nonuniform (e.g., Goldhirsch and Zanetti, 1993; McNamara and Young, 1994; Kudrolli et al., 1997; Goldhirsch, 2003). Recently, Möbius (2006) and Royer et al. (2009) carried out experiments using freely falling granular streams in a vacuum and indicated that cluster formation also occurred even in the gravity field. Based on these phenomena, in this paper, we consider

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the formation process of rays such that spatial non-uniform patterns are formed from the collisions between ejecta particles. First, we report the results of impact experiments with granular targets; we show the spatial distributions of granular materials during its flight after impacts, taking consecutive images of ejecta by a high-speed camera. Then, we compare the results of the experiments and some lunar rays based on the Fourier transformation analysis. Moreover, numerical simulations show that inelastic properties of ejected particles are important for the formation of clear patterns in ejecta curtains.

It is noted that, though the presence of air certainly affects ejecta emplacement (e.g., Schultz, 1992; Barnouin-Jha and Schultz, 1996, 1998; Barnouin-Jha et al., 1999; Suzuki et al., 2013), the effects of air are not considered in this work.

2. Experimental methods

We carried out impact experiments with an air gun at University of Occupational and Environmental Health. Cylindrical aluminum projectiles with a diameter of 10 mm and a height of 10 mm (2.1 g in mass) were accelerated and impacted on the surface of granular targets with an angle of 90° at $\sim$30–110 m s^{-1}. We used three kinds of granular materials as targets shown in Fig. 2: (a) spherical glass-beads with a size of 90–110 μm and a bulk density ρ_{bulk} of 1.44 g cm^{-3}, (b) "garden" sands with a size of 200–500 μm and ρ_{bulk} of 1.39 g cm^{-3}, which have various shapes and compositions, and (c) silica sands (SiO_2) with a size of 100–300 μm, ρ_{bulk} of 1.32 g cm^{-3}, and irregular shapes. These targets were poured into a bowl, which was hemispherical (almost round on the bottom) with a radius of 11 cm and set in a vacuum chamber using two angle brackets at the sides. We carried out 2 shots for glass beads, 1 shot for garden sand, and 3 shots for silica sands. Ambient pressures[1] were 200–600 Pa, except one shot for silica sands, where the pressure was 2 kPa. Ejecta motion was observed using a high-speed video camera (MEMRECAM fxK4, nac image technology) with a framing speed of 2000 frames per second and an exposure time of 10 or 20 μs.

3. Results

Fig. 3 shows consecutive images of a glass-beads target. A projectile from the top impacted perpendicularly onto the surface of the target with an impact velocity of 94.7 m s^{-1}. It is clearly seen in each frame that the spatial distribution of ejecta is a "mesh" pattern loosely woven with spaces like a net.

In Fig. 4a, we show three ejecta distributions, which are taken along three black horizontal lines, A, B, and C, in the lower-left panel in Fig. 3 with a length of 512 pixels (87 mm). The horizontal axis is the spatial length. The curves offset from each other on the vertical axis to avoid crossovers. The distributions are oscillatory. As the height from the original target surface increases ($C < B < A$), the lengths between peaks appear larger. We analyze these distributions using Fourier transformation to investigate their periodic structures. The obtained spectra are shown in Fig. 4b. The vertical axis is the natural logarithm of the square of the amplitude F, and the horizontal axis is frequency k in a unit of mm^{-1}; these are power spectra. We plot the data at k less than 0.74 mm^{-1}, where the signal is higher enough than the noise level ($\ln(F^2) \sim 4$–5). Though there is large scatter, each spectrum shows a linear decrease with k. We fit $\ln(F^2) = \alpha - \beta k$ (i.e., a straight line in this plot) to the data, where α and β are fitting parameters; this is an exponential type function. We consider the parameter β, the expected value of intervals between peaks, as a characteristic length λ_{c} of the sizes of spaces between meshes. In Fig. 4c, the obtained λ_{c} (=β) is shown against the distance from ejection point d, which is approximately estimated with the height from the target surface divided by $\sin(\pi/4)$, assuming an ejection angle of $\pi/4$ rad (e.g., Melosh, 1989). We also plot some results from the spectra of the other experiments with different conditions of glass beads at 44.6 m s^{-1}, garden sand at 101 m s^{-1}, silica sands at 103.0, 29.7, and 111.9 m s^{-1}, at various times after impact, which we picked to cover the distance range. Fig. 4c shows that the characteristic length λ_c increases with d and appears to depend only on d, regardless of the time after the impacts and the impact conditions, including the case with a higher ambient pressure of 2 kPa, silica sand at 111.9 m s^{-1}. Then, we define an "angle" θ_{c} between meshes as, λ_{c}/d in a unit of radian or $(\lambda_{\mathrm{c}}/d)(180/\pi)$ in degree. Fig. 4d indicates θ_{c} in a unit of degree. The horizontal axis is d normalized by crater diameters. Unfortunately, we did not observe the accurate crater diameters in the experiments due to our small vacuum chamber and small bowl that contained the target sands. Hence, instead, we use the calculated crater diameters, $1.32\pi_2^{-0.14}(m_{\mathrm{p}}/\rho_{\mathrm{bulk}})^{1/3}$ for glass beads, obtained by in Suzuki et al. (2013), and $1.4\pi_2^{-0.16}(m_{\mathrm{p}}/\rho_{\mathrm{bulk}})^{1/3}$ for garden and silica sands, in Schmidt (1980) and Melosh (1989), where $\pi_2 = 1.61gD_{\mathrm{p}}/v_{\mathrm{i}}^2$, and g, D_{p}, v_{i}, and m_{p}, are gravity constant, projectile diameter, impact velocity, and projectile mass, respectively. It appears that θ_{c} is almost constant $\sim$3–5° regardless of impact and target conditions. A constant angle implies that the pattern expands geometrically and does not evolve; the formation process in ejecta had finished at the observation time. Also, the independence of the target particles suggests that the inelastic properties, which would be related with the size, shape, and composition of target particles, do not influence the characteristic angle of the pattern. Finally, we note a projection effect. Since the image of the mesh-pattern taken by the camera is a projection onto a two-dimensional plane, the lengths between peaks in the horizontal direction on the images are smaller than its real values at, in particular, the outer parts. This effect would be more serious at the lower horizontal lines (near the target surface) when the length of the lines is constant. We evaluate this effect as, at most $\sim$5%, comparing Fourier spectra obtained from a simple sine curve along an arc and its projection onto a line.

4. Discussion

4.1. Crater rays on the Moon

We analyzed lunar rays around two similar sized craters, Glushko (Fig. 1a) and Kepler (Fig. 1b). We select these craters because some rays around these craters lay on lunar mare and are relatively clear due to high contrast. The distributions of the rays along three lines, 1, 2, and 3, for Glushko crater (Fig. 1a) with a length of 128 pixels (97.3 km) are shown in Fig. 5a. The distributions are oscillatory curves. We carried out Fourier transformation analysis and the power spectra were obtained. Fig. 5b shows the spectra as a function of frequency k in a unit of km^{-1}. We plot the spectra at k less than 0.33 km^{-1} (the noise level is $\ln(F^2) \sim 2$–3). Each spectrum has large scatter, but decreases linearly with frequency; this feature is similar to the experimental results. We considered the slope of the spectra β as a characteristic length λ_{c} and obtained β (=λ_{c}) by linear

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[1] Reynolds number $Re = \rho_{\mathrm{g}} x_{\mathrm{p}} v_{\mathrm{p}}/\eta$ (ρ_{g}, η, x_{p}, and v_{p} are the density and viscosity of residual air, the size of target particles, and ejection velocity, respectively) is an order of $\sim$1 at $v_{\mathrm{p}} \sim 10$ m/s in our experimental conditions. Though this value is, strictly speaking, slightly higher than the appropriate Re for Stokes law ($<\sim$0.1), we evaluate the aerodynamic drag on target particles using Stokes law, because the difference between the drag force and Stokes law is less than a factor of $\sim$1.5 at $Re \sim 1$ (e.g., Fig. 34 in Landau and Lifshitz, 1987). The characteristic time constant of the gas drag as $2\rho_{\mathrm{p}} {x_{\mathrm{p}}}^2/(9\eta)$ (ρ_{p} is the density of the particles) is $\sim$0.1–1 s for $x_{\mathrm{p}} \sim 100$ μm, which is longer than our observation time scale of an order of $\sim$10 ms.