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A new model of continuous dust production from the lunar surface

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Abstract. We estimate the production rate of lunar ejecta escaping from the Moon, taking into account the probable surface condition, i.e. the regolith layer. The production of lunar ejecta from a particulate surface is more effective than that from a hard surface. In our model for a particulate surface, the production rate is estimated to be about 10^{-3}kg s^{-1}, about 20 times higher than that calculated by Alexander et al. (1984) for the hard surface model. According to previous studies based on the hard surface model, lunar ejecta with sizes greater than a few μm cannot escape from the Moon. Our new results suggest that, in addition to micron- and submicron-sized ejecta, lunar ejecta with radii larger than tens of μm can escape from the Moon. These large grains may contribute to the IDPs collected in the upper atmosphere of the Earth.

Key words: Moon – planets and satellites: general

1. Introduction

Continuous bombardment by interplanetary meteoroids on airless bodies, such as asteroids and planetary satellites, increases the amount of dust in the vicinity of the bodies, and can be a source of interplanetary dust (e.g. Alexander et al. 1984; Ishimoto 1996; Yamamoto & Mukai 1996; Krüger et al. 1999). The orbits of the impact ejecta that have sufficient ejection velocity to escape from a parent body evolve under the influences of gravitational forces, mutual collisions, solar radiation pressure, the Poynting-Robertson effect, and electromagnetic forces in space. These dynamical processes depend strongly on the size as well as the shape and material content of the grains. In order to study the contribution of impact ejecta to the interplanetary dust population and to the formation of planetary dust rings, it is important to investigate how the production process depends on the size of the ejecta.

Many observations and in-situ measurements have revealed that in reality the surfaces of airless bodies are covered by regolith layers. While large meteoroids excavate deeper hard rock regions, the continuous impacts by interplanetary meteoroids, which provide a continuous flux of impact ejecta, produce craters in the regolith layer. It is expected that the size distribution of the impact ejecta emitted from the regolith surface is related to that of the grains in the regolith layer. However, there is no direct information on the grain size distribution of the regolith layers in asteroids and planetary satellites. On the other hand, the size distribution of grains in the lunar soil returned from the Moon has been well investigated (e.g. McKay et al. 1991). By using the lunar soil data, the contribution of impact ejecta from the Moon (lunar ejecta) to the dust population near the Earth can be quantified with useful precision. The study of the contribution of lunar ejecta to the dust population in the Earth-Moon system could provide clues as to the contribution of impact ejecta from asteroids and other planetary satellites to the interplanetary dust population, or about the formation of planetary dust rings.

In previous studies of lunar ejecta, the surface of the Moon was treated as hard rock, and a velocity distribution of ejecta ejected from hard surfaces was incorporated (e.g. Gault et al. 1963; Alexander et al. 1984; Yamamoto & Mukai 1996). Alexander et al. (1984) formulated the cumulative flux of lunar ejecta by using the results of impact experiments with rocky targets. Their model assumes that the size distribution of lunar ejecta is $n_{\rm esc}(a) \propto a^q$, where a is the radius of the lunar ejecta, and the power law index q is $3.43 - 3.49$, obtained from experiments of impacts onto rocky targets (e.g. Zook et al. 1984). In particular, in the Alexander et al. model, the size distribution of lunar ejecta produced by the impacts of interplanetary meteoroids with various sizes is assumed to be the same as that of fragments produced by the single impact of one particle. On the other hand, Yamamoto & Mukai (1996) derived the cumulative flux of lunar ejecta ejected from hard surfaces by summing all the escaping ejecta produced by impacting particles with various sizes. In the models of both Alexander et al. (1984) and Yamamoto & Mukai (1996), lunar ejecta with radii larger than a few μm cannot escape from the Moon because of their low ejection velocities.

In this study, the lunar surface is treated as a particulate surface. The major part of the interplanetary meteoritic mass impacting on the Moon is in particles with masses $m_{\rm i}$ ranging from 10^{-13} to 10^{-1}kg (Grün et al. 1985, Fig. 3), which are the largest contributors to the continuous production of lunar ejecta. The radii of these meteorites range from a few microns to a few centimeters. This size range is similar to that of the soil sample from the lunar regolith (McKay et al. 1991). If the size of the grains at the impact site is smaller than that of the impacting particle, cratering on a particulate surface should be considered when investigating the ejecta production process. On the other hand, a very small impactor could hit an individual grain, and the process could become that of the hard surface case. However, most of the small impactors are more likely to tunnel into the regolith. When a small impactor actually hits a solid particle, the location of impact could be either in the middle of the particle, or anywhere along its side; the impact ejecta may then be unable to escape because it may not be ejected upwards, and may hit the particles above or in the area surrounding the impact point. Thus the process of small grains impacting onto a hard surface may contribute very little to the production of lunar ejecta from the regolith surface, compared with that for a particulate surface. We therefore consider the production of lunar ejecta only for the case of a particulate surface.

In Sect. 2, we first derive the mass production rate of lunar ejecta for a particulate surface, and then compare it with previous results for a hard surface. We refer to crater scaling formulae (e.g. Holsapple & Schmidt 1982; Schmidt & Holsapple 1982; Housen et al. 1983) and recent experimental results on regolith-like targets (Yamamoto & Nakamura 1997). Based on the mass production rate calculated in Sect. 2, we estimate in Sect. 3 the cumulative flux of lunar ejecta as a function of ejecta size. We assume that the size distribution of the lunar ejecta is related to that of the lunar soil sample (McKay et al. 1991). The discussion and summary of our results are presented in Sects. 3 and 4, respectively.

2. Mass production rate of lunar ejecta

In this section, we estimate the mass production rate of the lunar ejecta, produced by continuous impacts of interplanetary meteoroids, with ejection velocities v_e higher than the lunar escape velocity v_esc.

2.1. Model of velocity distribution of powdery ejecta

The amount of ejecta escaping from the Moon depends on the velocity distribution of the ejecta and on gravity. For a particulate surface, the effect of gravity dominates the cratering processes; this is referred to as the gravity regime (e.g. Housen et al. 1983). For the gravity regime, Housen et al. (1983) formulated a scaling relationship for the velocity distribution of the powdery ejecta by assuming a point source of energy and momentum. The volume $V(>v_\mathrm{e})$ of ejecta with velocities higher than v_e is expressed as,

$$\frac{V(>v_\mathrm{e})}{R^3} = K_3 \left(\frac{v_e}{\sqrt{gR}}\right)^{-e_\mathrm{v}}, \tag{1}$$

where g is the gravitational acceleration, R a crater radius, K_3 a constant, and the power-law exponent e_v is $e_\mathrm{v} = \frac{6\alpha}{3-\alpha}$, where the parameter α is related to the energy and momentum coupling in the cratering process. Housen et al. (1983) derived $K_3 = 0.32$ and $\alpha \sim 0.5$ by using the low velocity (∼m s^{-1}) data from experiments of impacts onto sand targets. On the other hand, Yamamoto & Nakamura (1997) reported that the total volume of powdery ejecta with $v_\mathrm{e} > 0.3$ km s^{-1} lies below that extrapolated from the lower velocity data of Housen et al. (1983). The scaling law found by Housen et al. (1983) is almost universally the result of the point source assumption, which is not valid for high-speed ejecta. Neither the relation of $e_\mathrm{v} = \frac{6\alpha}{3-\alpha}$ nor $\alpha \sim 0.5$ derived by Housen et al. (1983) is appropriate for ejecta with high ejection velocities. Therefore, to model the velocity distribution of powdery ejecta for a wide range of velocities, we use a continuous curve with an increasingly negative slope, which intersects the power-law relation of Housen et al. (1983) at lower velocities, and fits the experimental data of Yamamoto & Nakamura (1997) at higher velocities. Eq. (1) is modified as

$$\frac{V(>v_\mathrm{e})}{R^3} = K_3 \left(\frac{v_\mathrm{e}}{\sqrt{gR}}\right)^{-\frac{6\alpha}{3-\alpha}h(v_\mathrm{e})}, \tag{2}$$

where

$$h(v_\mathrm{e}) = 1 + \phi \exp\left(-\frac{\epsilon}{v_\mathrm{e}/\sqrt{gR}}\right), \tag{3}$$

and ϕ and ϵ are parameters. When $v_\mathrm{e}/\sqrt{gR} \ll \epsilon$, $h(v_\mathrm{e}) \sim 1$, indicating that Eq. (2) approaches the scaling law in Eq. (1). The crater radius R for a sand target is given by the following relation (Schmidt & Holsapple 1982):

$$R\left(\frac{\rho_\mathrm{b}}{m_\mathrm{i}}\right)^{1/3} \left\{\frac{g}{v_\mathrm{i}^2/2}\left(\frac{m_\mathrm{i}}{\rho_\mathrm{i}}\right)^{1/3}\right\}^{\alpha/3} = K_0 \tag{4}$$

where v_i is the impact velocity of the projectile, m_i is the mass of the projectile, ρ_b is the bulk density of the layer of particles, ρ_i is the density of the projectile, and K_0 is a constant. From Eqs. (2) and (4), the total mass $M(>v_\mathrm{e}) = \rho_\mathrm{b} V(>v_\mathrm{e})$ of the ejecta with velocities higher than v_e, produced by the impact of a particle with mass m_i, is derived as,

$$\begin{aligned} M(>v_e) \;=\; & K_3 \left\{K_0^3 (v_\mathrm{i}^2/2)^\alpha\right\}^{\frac{3}{3-\alpha}z(v_\mathrm{e})} \left(\frac{\rho_\mathrm{i}^{z(v_\mathrm{e})}}{\rho_\mathrm{b}^{h(v_\mathrm{e})}}\right)^{\frac{\alpha}{3-\alpha}} \\ & \times g^{\alpha(h(v_\mathrm{e})-1)} m_\mathrm{i}^{z(v_\mathrm{e})} v_\mathrm{e}^{-\frac{6\alpha}{3-\alpha}h(v_\mathrm{e})}, \end{aligned} \tag{5}$$

where

$$z(v_\mathrm{e}) = 1 + \frac{\phi\alpha}{3} \exp\left(-\frac{\epsilon}{v_\mathrm{e}/\sqrt{gR}}\right). \tag{6}$$

2.2. Production rate of lunar ejecta escaping from the Moon

Using the results of impact experiments with sand targets, Schmidt & Holsapple (1982) estimated $\alpha \sim 0.5$ and $K_0 = 0.847$ for Eq. (4). Housen et al. (1983) also derived $K_3 = 0.32$ and $\alpha \sim 0.5$. From Fig. 8 in Yamamoto & Nakamura (1997), it is expected that ϵ ranges from about 10 to a few hundred. When we fit the data of Yamamoto & Nakamura (1997) to Eq. (2), adopting $K_3 = 0.32$ and $\alpha = 0.50$, we obtain $\phi = 0.30$, which is almost independent of ϵ as long as $\epsilon <$ a few hundred. Therefore, we take $\epsilon = 10$ and $\phi = 0.30$. We take the gravitational acceleration as $g = 1.6$ m s^{-1}, the effective meteoroid density as $\rho_\mathrm{i} = 2.5 \times 10^3$ kg m^{-3} (Grün et. al 1985), and the density of lunar regolith grains as $\rho_\mathrm{g} = 3.0 \times 10^3$kg m^{-3} (Carrier et al. 1991). The bulk density ρ_b of the regolith layers depends on the porosity. We assume that the porosity is 0.5 (Yen & Chaki 1992) and adopt $\rho_\mathrm{b} = 1.5 \times 10^3$ kg m^{-3}. When $v_\mathrm{e} = v_\mathrm{esc}$, where the lunar escape velocity is $v_\mathrm{esc} = 2.38$ km s^{-1}, we get $h(v_\mathrm{esc}) \sim 1.30$ and $z(v_\mathrm{esc}) \sim 1.05$. Substituting these values into Eq. (5), we obtain

$$M(> v_\mathrm{esc}) = 4.9 \times 10^{-7} v_\mathrm{i}^{1.26} m_\mathrm{i}^{1.05}. \quad (7)$$

Using Eq. (7), we calculate the mass production rate $\dot{M}_\mathrm{total}(> v_\mathrm{esc})$ of the lunar ejecta as,

$$\dot{M}_\mathrm{total}(> v_\mathrm{esc}) = A \int_{m_{\mathrm{i}0}}^{m_{\mathrm{i}1}} f(m_\mathrm{i}) M(> v_\mathrm{esc}) dm_\mathrm{i}, \quad (8)$$

where $f(m_\mathrm{i})dm_\mathrm{i}$ is the flux of interplanetary meteoroids with masses between m_i and $m_\mathrm{i} + dm_\mathrm{i}$ derived by Grün et al. (1985); $m_{\mathrm{i}1}$ and $m_{\mathrm{i}0}$ are, respectively, the maximum and minimum mass of the interplanetary meteoroids, and $A = 3.8 \times 10^{13}$m^2 is the total area of the lunar surface. Since the major part of the interplanetary meteoric mass is in particles with $10^{-13} < m_\mathrm{i} < 10^{-1}$kg, we set $m_{\mathrm{i}0} = 10^{-13}$kg and $m_{\mathrm{i}1} = 10^{-1}$kg. According to Zook (1975), the impact velocities onto the Moon range from 2.78 km s^{-1} to more than 50 km s^{-1}. In their analysis of the flux of the interplanetary meteoroids, Grün et al. (1985) assumed an effective velocity amongst the different meteoroids of 20 km s^{-1} onto the moon. Since some of the excavated material melts during the hypervelocity impact with $v_\mathrm{i} = 20$ km s^{-1} (see Melosh 1989), the lunar ejecta that might escape from the Moon could suffer from melting. Although they would solidify rapidly, it is not clear how the melted ejecta change the shape of the original size distribution.

According to Ahrens & O'Keefe (1977), when $v_\mathrm{i} = 5$ km s^{-1}, the peak shock pressure is slightly lower than the threshold pressure to induce melting. Although the majority of bombardments with an average impact velocity of 20 km s^{-1} induces melting, the impacts with $v_\mathrm{i} \leq 5$ km s^{-1} can provide lunar ejecta without melting. Consequently, we estimate the production rate of lunar ejecta for both $v_\mathrm{i} = 5$ km s^{-1} and $v_\mathrm{i} = 20$ km s^{-1}. According to Fig. 3 in Zook (1975), the fraction of interplanetary meteoroids with $v_\mathrm{i} \leq 5$ km s^{-1} is a few percent. For simplicity, the absolute magnitude of the meteoroidal flux with $v_\mathrm{i} = 5$ km s^{-1} is assumed to be 1% of that of the flux with $v_\mathrm{i} = 20$ km s^{-1}. The production rates of lunar ejecta calculated below for $v_\mathrm{i} = 5$ km s^{-1} and 20 km s^{-1} would correspond to the lower and the upper estimates.

Table 1 shows that the resulting mass production rate $\dot{M}_\mathrm{total}(> v_\mathrm{esc})$ is up to 10^{-3}kg s^{-1}. Alexander et al. (1984) have estimated that the mass production rate of the lunar ejecta is 4.8×10^{-5}kg s^{-1}, using the results of impact experiments with rocky targets with $v_\mathrm{i} \sim 20$ km s^{-1}. The production rate calculated here with $v_\mathrm{i} = 20$ km s^{-1} is about 20 times higher than that estimated by Alexander et al.. The production of lunar ejecta from a particulate surface is more effective than that from a hard surface.

Table 1. The mass production rates $\dot{M}_\mathrm{total}$ of lunar ejecta ejected from a particulate surface, for $v_\mathrm{i} = 5$ and 20 km s^{-1}. For comparison, the result from the hard surface model by Alexander et al. (1984) ($v_\mathrm{i} \sim 20$ km s^{-1}) is also shown.

	production rate of lunar ejecta [kg s^{-1}]
particulate surface	1.0 $\times 10^{-3}$ ($v_\mathrm{i} = 20$ km s^{-1})
particulate surface	2.0 $\times 10^{-6}$ ($v_\mathrm{i} = 5$ km s^{-1})
Alexander et al. (1984) model	4.8×10^{-5} ($v_\mathrm{i} = 20$ km s^{-1})

3. Production rate of lunar ejecta as a function of size

In this section, we estimate the production rate of lunar ejecta as a function of ejecta size. Namely, we determine the size distribution of lunar ejecta with $M(> v_\mathrm{esc})$ estimated in Eq. (7) by the following.

It is likely that the size distribution of lunar ejecta is related to that of the lunar soil. We use three typical lunar soil samples, that of 71501,1 Mare, 73261,1 Massif, and 78421,1 Massif of the Apollo 17 soils (McKay et al. 1991, Fig. 7.9). Some of the original grains are comminuted during the cratering process (Cintala & Hörz 1990; 1992). The comminution of the original grains changes the size distribution in the lunar soil. According to Cintala & Hörz (1990), the comminuted target mass M_c due to the impact of a particle with radius a_i and velocity v_i is given by an equation of the form

$$M_\mathrm{c} = 1.2 \times 10^{-2} \rho_\mathrm{i}^{5.72} \rho_\mathrm{b}^{-5.20} (2a_\mathrm{i})^{1.46} k^{0.18} \times a_\mathrm{av}^{0.21} a_\mathrm{so}^{-0.29} (\rho_b V_\mathrm{total})^{0.48} \left(\frac{v_\mathrm{i}}{C_\mathrm{g}}\right)^{0.65}, \quad (9)$$

where k and a_av are, respectively, the mean crystal size and the mean grain size of the lunar soil, a_so is sorting of the grains (that is the standard deviation of the size-frequency distribution), and C_g is the sound speed of the grains. The value of k for the targets used by Cintala & Hörz (1990) ranges from 0.35 mm to 2.5 mm, depending on the grain size. Since the value of M_c is insensitive to the value of k in Eq. (9), we set $k = 1.0$ mm. The total ejecta volume $\rho_\mathrm{b} V_\mathrm{total}$ in the gravity regime is obtained as,

$$\frac{\rho_b V_\mathrm{total}}{m_\mathrm{i}} = K_1 \left\{ \frac{g}{v_\mathrm{i}^2/2} \left(\frac{m_\mathrm{i}}{\rho_\mathrm{i}}\right)^{1/3} \right\}^{-\alpha}, \quad (10)$$

where we use 0.23 and 0.50 for the constants K_1 and α respectively (Schmidt & Holsapple 1982). When we set $C_\mathrm{g} = 2.6 \times 10^3$m s^{-1} for basalt (Melosh 1989), $\rho_\mathrm{b} = 1.5 \times 10^3$ kg m^{-3}, $\rho_\mathrm{i} = 2.5 \times 10^3$ kg m^{-3}, and $a_\mathrm{i} = (3m_\mathrm{i}/4\pi\rho_\mathrm{i})^{1/3}$, the ratio η of M_c to $\rho_\mathrm{b} V_\mathrm{total}$ is

$$\eta = \frac{M_\mathrm{c}}{\rho_b V_\mathrm{total}} \sim 2 \times 10^{-3} a_\mathrm{av}^{0.21} a_\mathrm{so}^{-0.29} m_\mathrm{i}^{0.05}, \quad (11)$$

for both $v_\mathrm{i} = 5$ and 20 km s^{-1}. The difference between the results for $v_\mathrm{i} = 5$ and 20 km s^{-1} is negligibly small. The values a_av and a_so for the lunar soil sample used here are $42\mu\mathrm{m} < a_\mathrm{av} < 74\mu\mathrm{m}$ and $0.15\mathrm{mm} < a_\mathrm{so} < 0.24\mathrm{mm}$ (Carrier et al. 1991). Fig. 1 shows that the value of η calculated by Eq. (11)

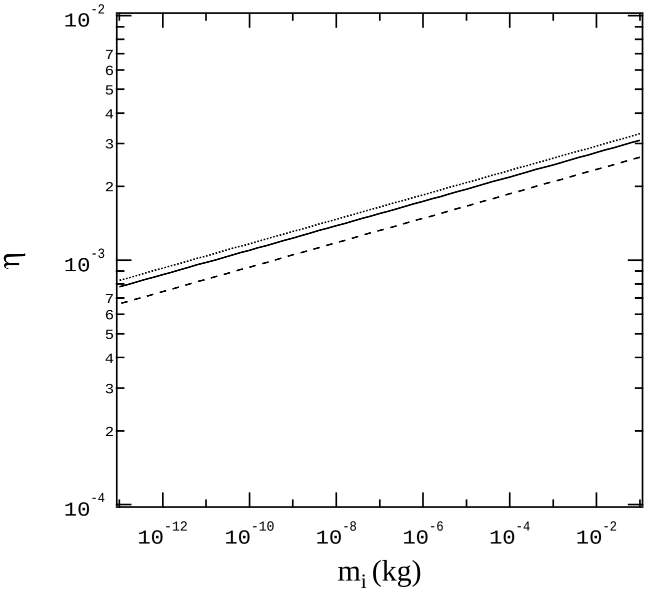

Fig. 1. Ratio η of the comminuted target mass to the total excavated mass. The solid line, dotted line, and dashed line correspond to 71501,1 Mare, 73261,1 Massif, and 78421,1 Massif (McKay et al. 1991) respectively.

ranges from 6×10^{-4} to 3×10^{-3}, depending on $a_{\rm av}$ and $a_{\rm so}$ as well as $m_{\rm i}$. We find that the total mass of the lunar ejecta is smaller than that of the comminuted grains, i.e. $M(> v_{\rm esc}) < M_{\rm c}$. From Eqs. (7), (10), and (11), the ratio ζ of $M(> v_{\rm esc})$ to $M_{\rm c}$ is

$$\zeta = \frac{M(> v_{\rm esc})}{M_{\rm c}} \sim 4 \times 10^{-3} a_{\rm av}^{-0.21} a_{\rm so}^{0.29} m_{\rm i}^{0.16}, \tag{12}$$

for both $v_{\rm i} = 5$ and $v_{\rm i} = 20$ km s^{-1}. Eq. (12) shows that $\zeta \ll 1$, as long as $10^{-13} \le m_{\rm i} \le 10^{-1}$kg. If the velocity of the fragments produced by the comminution is higher than that of the intact grains, most of the lunar ejecta are the comminuted components. However, it is likely that the lunar ejecta are not only comminuted fragments but are also the original lunar soil grains. From their experiments of impacts onto regolith targets, Yamamoto & Nakamura (1997) reported that most of the ejecta with ejection velocities higher than a few hundred m s^{-1} were intact powders without comminution. Since the relationship between the size and velocity distributions of the ejecta has not been investigated in previous impact experiments involving regolith targets, it is difficult to estimate how many intact grains and comminuted grains have sufficient ejection velocity to escape from the Moon. Therefore, we examine the cases of comminuted grains and intact lunar soil grains separately. If all the lunar ejecta are the comminuted component, the largest lunar ejectum is sufficiently smaller than the original lunar grain, as shown in Sect. 3.1. On the other hand, if the size distribution of the lunar ejecta is the same as that of the lunar soil samples, the larger lunar ejecta can escape from the Moon.

3.1. Model for comminuted grains

The lunar ejecta are assumed to be fragments due to the comminution of grains in the regolith layer. We assume that the fraction of comminuted grains amongst the lunar soil grains is independent of grain size, and that the finer fragments produced by the comminution have higher ejection velocities. The maximum size of the lunar ejecta depends on the peak pressure loaded on the comminuted grains. Since this model calculates the lower estimate of the maximum size of the lunar ejecta, a grain is assumed to be comminuted under the initial (maximum) peak pressure of the impact. The number $n_{\rm f}(a_{\rm f}, a_{\rm g})da_{\rm f}$ of comminuted fragments with radii ranging from $a_{\rm f}$ to $a_{\rm f} + da_{\rm f}$ is assumed to be

$$n_{\rm f}(a_{\rm f}, a_{\rm g})da_{\rm f} = K(a_{\rm g}) a_{\rm f}^{3\beta+2} da_{\rm f}, \tag{13}$$

where $K(a_{\rm g})$ is a constant and $a_{\rm g}$ is the radius of the original grain before comminution. When the impact stress in the grain is sufficiently high, the power law index approaches $\beta = -5/3$ (Mizutani et al. 1990), i.e. $n_{\rm f}(a_{\rm f}, a_{\rm g}) = K(a_{\rm g}) a_{\rm f}^{-3}$. Assuming a spherical shape for the lunar soil grains, the mass of comminuted grains is $\eta N(a_{\rm g}) da_{\rm g} \times 4\pi \rho_{\rm g} a_{\rm g}^3/3$ where $N(a_{\rm g})da_{\rm g}$ is the number of grains in the lunar soil sample with radii ranging from $a_{\rm g}$ to $a_{\rm g} + da_{\rm g}$, given in McKay et al. (1991). The value of $K(a_{\rm g})$ is determined by

$$\int_{a_{\rm f0}}^{a_{\rm f1}} a_{\rm f}^3 n_{\rm f}(a_{\rm f}, a_{\rm g}) da_{\rm f} = a_{\rm g}^3 \eta N(a_{\rm g}), \tag{14}$$

where $a_{\rm f1}$ and $a_{\rm f0}$ are, respectively, the maximum and the minimum radius of the comminuted fragments. From Eqs. (13) and (14), the number of comminuted fragments is obtained as,

$$n_{\rm f}(a_{\rm f}, a_{\rm g}) da_{\rm g} = \frac{a_{\rm g}^3 \eta N(a_{\rm g}) da_{\rm g}}{a_{\rm f1} - a_{\rm f0}} a_{\rm f}^{-3}. \tag{15}$$

The γ of $a_{\rm f1}$ to $a_{\rm g}$ depends on the magnitude $P_{\rm I}$ of the non-dimensional impact stress (NDIS), which is estimated by the following relation (Mizutani et al. 1990):

$$\gamma^3 = \frac{a_{\rm f1}^3}{a_{\rm g}^3} = 10^{-1.627} P_I^{-0.936}, \tag{16}$$

in which we assume that the attenuation of the peak pressure P_0 in the grain is negligibly small, and that $P_{\rm I} = P_0/Y$, where P_0 is the initial peak pressure and Y is the target tensile strength. The pressure P_0 due to the impact of a projectile with velocity $v_{\rm i}$ is given by Mizutani et al. (1990) as,

$$P_0 = \frac{1}{2} \xi \rho_{\rm b} C_{\rm t} v_{\rm i} (1 + \frac{1}{2} s_{\rm t} \xi \frac{v_{\rm i}}{C_{\rm t}}), \tag{17}$$

where $C_{\rm t}$ is the bulk sound speed (in dimension of velocity), $s_{\rm t}$ is a constant, and the parameter ξ, which is related to shock impedance matching, is in the order of 1. When we set $C_{\rm t} = 1.7 \times 10^3$m s^{-1}, $s_{\rm t} = 1.3$ for dry sand (Melosh 1989), $\rho_{\rm b} = 1.5 \times 10^3$kg m^{-3}, $\xi = 1.0$, and $Y = 10^7$ Pa for basalt, we estimate $\gamma \sim 0.01$ for $v_{\rm i} = 20$ km s^{-1} and $\gamma \sim 0.03$ for $v_{\rm i} = 5$ km s^{-1}. We set $a_{\rm f0} = 0.1\mu$m because Asada (1985) has detected fine fragments with sizes of about $0.1\mu m$ in his impact experiments with basalt targets. We neglect the small fragments with $a_{\rm f} < a_{\rm f0}$.

Using Eq. (15), we calculate the size distribution $n_{\rm c}(a_{\rm f})$ of the fragments produced by the comminution of lunar soil grains, as

$$n_{\rm c}(a_{\rm f}) = \int_{a_{\rm g0}}^{a_{\rm g1}} n_{\rm f}(a_{\rm f}, a_{\rm g}) da_{\rm g} = a_{\rm f}^{-3} \int_{a_{\rm g0}}^{a_{\rm g1}} \frac{a_{\rm g}^3 \eta N(a_{\rm g})}{a_{\rm f1} - a_{\rm f0}} da_{\rm g}, \quad (18)$$

where $a_{\rm g0} = a_{\rm f}/\gamma$ and $a_{\rm g1}$ are the minimum and the maximum radius of the lunar soil grains, respectively. Since we assume that the size of the grains in the regolith layer is smaller than that of the impacting particle, we set $a_{\rm g1} = a_{\rm i}$. By using $M(> v_{\rm esc})$ from Eq. (7) and $n_{\rm c}(a_{\rm f})$ from Eq. (18), the size distribution $n_{\rm esc}(a_{\rm f}, m_{\rm i})$ of the lunar ejecta is expressed as

$$n_{\rm esc}(a_{\rm f}, m_{\rm i}) = \frac{M(> v_{\rm esc})}{\int_{a_{\rm f0}}^{a_{\rm e1}} n_{\rm c}(a') \frac{4\pi\rho_{\rm g} a'^3}{3} da'} n_{\rm c}(a_{\rm f}) \quad (19)$$

where $a_{\rm e1}$ is the maximum radius of the fragments escaping from the Moon. Eq. (19) cancels out the value of η in Eq. (18). By using ζ from Eq. (12), $a_{\rm e1}$ is derived by the following relation:

$$\zeta = \frac{M(> v_{\rm esc})}{M_{\rm c}} = \frac{\int_{a_{\rm f0}}^{a_{\rm e1}} n_{\rm c}(a) a^3 da}{\int_{a_{\rm f0}}^{a_{\rm f1}} n_{\rm c}(a) a^3 da}. \quad (20)$$

From Eqs. (12) and (20), the maximum sizes $a_{\rm e1}$ of the lunar ejecta for $a_{\rm i}$ = 20 mm ($m_{\rm i} = 10^{-1}$ kg) are estimated to be $a_{\rm e1} \sim 2\mu$m for $v_{\rm i} = 5$ km s^{-1}, and $a_{\rm e1} \sim 0.8\mu$m for $v_{\rm i} = 20$ km s^{-1}.

The cumulative flux of the lunar ejecta $F(a_{\rm e})$ at the lunar surface is calculated by using Eq. (19), and $f(m_{\rm i})$ in Eq. (8), as

$$F(a_{\rm e}) = \int_{a_{\rm e}}^{\infty} da \int_{m_{\rm i0}}^{m_{\rm i1}} n_{\rm esc}(a, m_{\rm i}) f(m_{\rm i}) dm_{\rm i}, \quad (21)$$

where $m_{\rm i1} = 10^{-1}$ kg and $m_{\rm i0}$ is the minimum mass that can produce lunar ejecta with radius $a_{\rm e}$, calculated by using Eq. (20). Fig. 2 shows $F(a_{\rm e})$ calculated for the lunar soil samples of (a) 71501,1 Mare, (b) 73261,1 Massif, and (c) 78421,1 Massif, for both $v_{\rm i} = 20$ km s^{-1} (dashed curve) and $v_{\rm i} = 5$ km s^{-1} (dotted curve). For comparison, the cumulative flux model of interplanetary meteoroids (Grün et al. 1985) (solid curve) is also plotted in Fig. 2. The flux of the submicron-sized lunar ejecta due to the impacts by interplanetary meteoroids with $v_{\rm i} = 20$ km s^{-1} is much higher than that of the incoming interplanetary flux. In addition, the impacts by interplanetary meteoroids with $v_{\rm i} = 5$ km s^{-1} produce a large number of submicron-sized lunar ejecta. There is no significant difference between the fluxes calculated for the different target lunar soil samples.

3.2. Model for intact grains

Next, we assume that the lunar ejecta are the intact lunar soil grains, and that the ejection velocity is independent of the grain size. Since the lunar soil sample data have no grains with radii smaller than about 2μm (McKay et al. 1991), we consider only the lunar ejecta with radii larger than 2μm, i.e. $a_{\rm g0} = 2\mu$m. The size distribution $n_{\rm esc}(a_{\rm f}, m_{\rm i})$ of lunar ejecta produced by the impact of a meteoroid with mass $m_{\rm i}$ is calculated by

$$n_{\rm esc}(a_{\rm f}, m_{\rm i}) = \frac{M(> v_{\rm esc})}{\int_{a_{\rm g0}}^{a_{\rm g1}} N(a') \frac{4\pi\rho_{\rm g} a'^3}{3} da'} N(a_{\rm f}), \quad (22)$$

where $N(a)$ is given in McKay et al. (1991) and $a_{\rm g1} = a_{\rm i}$. Substituting Eq. (22) into Eq. (21), the cumulative flux $F(a_{\rm e})$ of lunar ejecta as a function of $a_{\rm e}$ is calculated. Since it is assumed for the particulate surface that the size of the impactor is larger than that of the grains in the regolith, we set $m_{\rm i0} = (3a_{\rm e}/4\pi\rho_{\rm g})^{1/3}$, and $m_{\rm i1} = 10^{-1}$ kg in Eq. (21). Fig. 3 shows that there are lunar ejecta with sizes larger than tens of μm escaping from the Moon. The flux of lunar ejecta produced by the impacts of the meteoroids with $v_{\rm i} = 20$km s^{-1} (dashed line) is comparable with that in the interplanetary flux model (Grün et al. 1985) (solid curve). In particular, when $v_{\rm i} = 20$ km s^{-1}, the flux of the submicron-sized lunar ejecta is higher than that of the in-

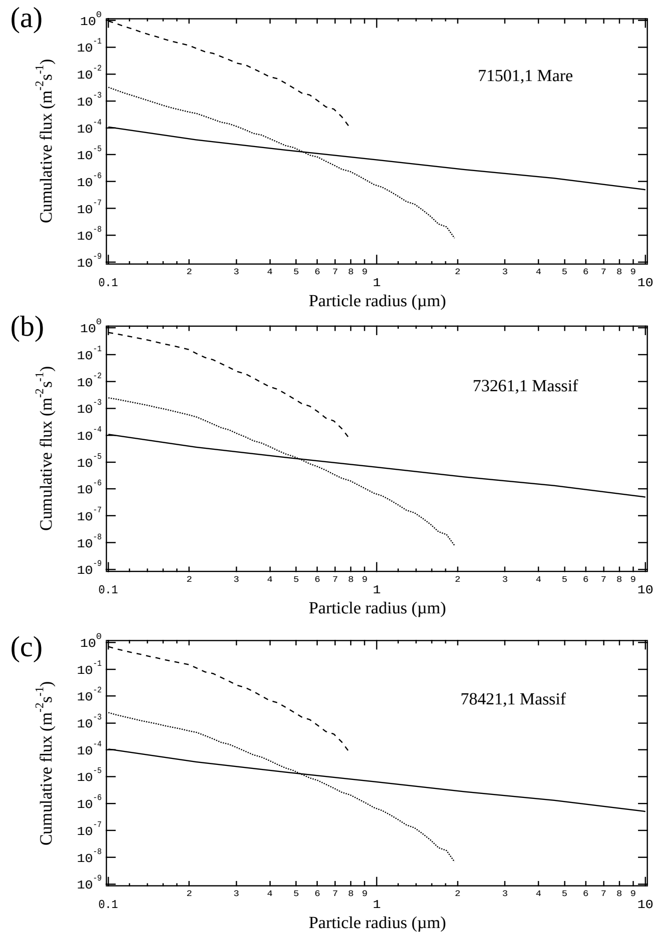

Fig. 2a – c. Cumulative flux of lunar ejecta at the lunar surface, for the comminuted grain model. The dashed curve and the dotted curve correspond to the upper estimate ($v_{\rm i} = 20$ km s^{-1}) and the lower estimate ($v_{\rm i} = 5$ km s^{-1}) respectively. We use three typical samples of lunar surface soil of **a** 71501,1 Mare, **b** 73261,1 Massif, and **c** 78421,1 Massif (McKay et al. 1991). For comparison, the interplanetary flux model (Grün et al. 1985) (solid curve) is also plotted.

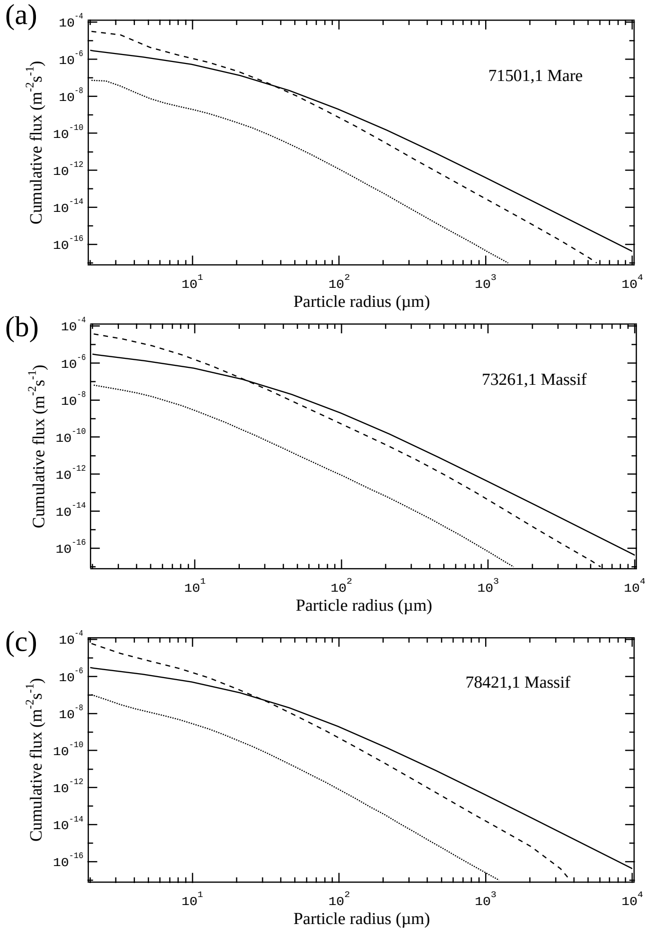

Fig. 3a – c. Cumulative flux of lunar ejecta at the lunar surface for the intact grain model. The dashed curve and the dotted curve correspond to the upper estimate ($v_{\rm i} = 20$ km s^{-1}) and the lower estimate ($v_{\rm i} = 5$ km s^{-1}) respectively. We use three typical samples of lunar surface soil of **a** 71501,1 Mare, **b** 73261,1 Massif, and **c** 78421,1 Massif (McKay et al. 1991). For comparison, the interplanetary flux model (Grün et al. 1985) (solid curve) is also plotted.

coming interplanetary flux. There is no significant difference between the fluxes calculated for the different target lunar soil samples.

3.3. Discussion

In the comminuted grain model, the largest lunar ejecta is about 2μm in size, produced by impacts of interplanetary meteoroids with $v_{\rm i} = 5$km s^{-1}. On the other hand, in the intact grain model, lunar ejecta with sizes larger than tens of μm can escape from the Moon. Previous results based on the hard surface model (Alexander et al. 1984; Yamamoto & Mukai 1996) have suggested that no lunar ejecta with radii larger than a few μm can escape from the Moon. In the comminuted grain model, the largest lunar ejecta is comparable in size to that in the hard surface model.

It is likely that in practice the cumulative flux of the lunar ejecta lies between that for the case of comminuted grains and that for the case of intact grains, although it is difficult to predict rigorously how many intact grains have enough ejection velocity to escape from the Moon as lunar ejecta. Based on the results of impact experiments with regolith targets by Yamamoto & Nakamura (1997), we calculated $M(> v_{\rm e})$ of Eq. (5) and $M_{\rm c}$ of Eq. (9). We found that the resulting total mass of the ejecta is smaller than the total mass of the comminuted grains, i.e. $M(> v_{\rm e}) < M_{\rm c}$ for the range of $v_{\rm e} \geq$ a few hundreds m s^{-1}. This is the same condition as shown above in Eq. (12), although the velocity range detected by Yamamoto & Nakamura (1997) is 0.3 km s^{-1} $\leq v_{\rm e} \leq 1.7$ km s^{-1}. Yamamoto & Nakamura (1997) reported that the fraction of comminution fragments was up to 10%. Most of the high- velocity ejecta detected in their experiments would be ejected from the powdery target without comminution. Therefore, it is expected that a large number of the original lunar soil grains could escape from the Moon. We conclude that, in addition to micron and submicron-sized lunar ejecta, lunar ejecta with radii larger than tens of μm can escape from the Moon.

4. Summary

We estimated the production rate of lunar ejecta escaping from the Moon, taking into account the lunar regolith surface. The resulting mass production rate of lunar ejecta is up to 10^{-3}kg s^{-1}, about 20 times higher than that in the hard surface model calculated by Alexander et al. (1984), based on the results of impact experiments with rocky targets. This indicates that the production of lunar ejecta from a particulate surface is more effective than that from a hard surface.

We then estimated the size distribution of lunar ejecta as a function of ejecta size for the case of a particulate surface. If the surface of the Moon is treated as a hard surface (Alexander et al. 1984; Yamamoto & Mukai 1996), grains with sizes greater than a few μm cannot escape from the Moon because of their low ejection velocities. On the other hand, for the case of a particulate surface, our model suggests that lunar ejecta with radii larger than tens of μm, as well as micron and submicron-sized ejecta, can escape from the Moon.

Lunar ejecta with sizes smaller than a few μm are significantly influenced by the solar radiation pressure (Burns et al. 1979), and some of them take hyperbolic orbits. On the other hand, lunar ejecta with sizes larger than tens of μm can enter into geocentric orbits, because the effect of solar radiation pressure is too small to change their orbits significantly. Therefore, the large ejecta ejected from the lunar regolith surface may form a dust population in the vicinity of the Earth. Some of the large lunar ejecta may arrive at the Earth and contribute to the IDPs collected in the upper atmosphere. The existence of lunar ejecta among particles collected in the upper atmosphere has not been confirmed. We hope that future measurements of dust near the Earth and the Moon will confirm their existence.

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