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Dust production by impacts of interstellar dust on Edgeworth-Kuiper Belt objects

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Abstract. We estimated the production rate of dust grains by the impacts of interstellar dust grains on Edgeworth-Kuiper Belt objects (EKOs). In this scenario, the impact ejecta become interplanetary dust particles with radii smaller than about 10 μm. If the EKOs have hard icy surfaces and there are $\sim 10^{13}$ of these with radii $\geq$0.1 km, the total dust production rate over the entire Edgeworth-Kuiper Belt ranges from 3.7×10^5g s^{-1} to 2.4×10^6g s^{-1}, depending on the adopted minimum ejection velocity (10 cm s^{-1} $\sim$10^3 cm s^{-1}). If the surfaces of EKOs are covered by a layer of icy particles with radii smaller than those of the incident dust grains, then the total dust production rate is enhanced slightly to about 3.1×10^7g s^{-1}. Adopting the different collisional parameters used by Stern (1996), we find that the production rate of dust grains with radii smaller than 10μm by mutual collisions of EKOs is between 8.6×10^4g s^{-1} and 2.9×10^7g s^{-1}. Therefore dust production due to the impacts by interstellar dust on EKOs is a significant source of interplanetary dust grains, at least for those far from the sun with radii smaller than about 10 μm.

Key words: minor plantes – interplanetary medium

1. Introduction

Meteoroid detectors on board Pioneer 10 and 11 recorded a near constant rate of impact by dust grains, which have moderately eccentric orbits with random inclinations, out to a distance of 18AU (Humes 1980). Recent space probes such as Ulysses and Galileo, furthermore, detected dust grains in the ecliptic plane at heliocentric distances between 0.7 and 5.4 AU, and in an almost perpendicular-plane from ecliptic latitude $-79°$ to $+79°$ (Grün et al. 1995a,b). Although these dust grains may originate from different sources of interplanetary dust, the variation of the impact flux of meteoroids with heliocentric distance suggests the existence of dust sources in the outer Solar System.

Active comets can be major contributors to these dust grains. However, since small dust grains released from active comets are likely to have large eccentricities, most of them escape from the Solar System due to solar radiation pressure forces (Mukai 1985). Therefore it is unlikely that active comets are a major source of interplanetary dust at large heliocentric distances.

Recently, it has been suggested that significant dust production occurs in the Edgeworth-Kuiper Belt due to the mutual collisions of Edgeworth-Kuiper Belt objects (EKOs) (e.g. Backman et al. 1995; Liou et al. 1996; Stern 1996). Jewitt & Luu (1995) estimated that about 3.5×10^4 objects with diameters larger than 100km exist in the Edgeworth-Kuiper Belt. Observations by the Hubble Space Telescope suggest that there are more than 2×10^8 Halley-sized objects in the region (Cochran et al. 1995). Duncan et al. (1995) estimated that, within 50 AU, the total number of comets in the Belt is roughly 5×10^9. It has been proposed that the collisions between these objects provide a significant amount of dust grains in the Edgeworth-Kuiper Belt. Stern (1996) estimated the production rate of collisional debris, and predicted a time-averaged mass supply rate of $3 \times 10^{16} \sim 10^{19}$g yr^{-1}, for collisional debris ranging from multi-kilometer blocks to fine dust.

The in situ measurements by the Ulysses spacecraft show that the stream of interstellar grains penetrates into the Solar System (Grün et al. 1993). In this paper, we propose that the impacts by such interstellar dust on EKOs produce a considerable amount of dust grains. EKOs are continuously bombarded by interstellar dust grains with high relative velocities ($\sim$ 26 km s^{-1}). Although the amount of target material excavated by the individual impacts of interstellar dust is smaller than the amount produced by collisions between large EKOs, impacts by interstellar dust grains occur more frequently. Moreover, all EKOs are bombarded by interstellar dust simultaneously, whereas mutual collisions of EKOs occur locally. As a consequence, the continuous impact by interstellar dust should provide a considerable amount of dust grains all over the Edgeworth-Kuiper Belt region.

In Sect. 2, we investigate dust production under two different surface conditions. In one model the surfaces are composed of hard icy material. In the other model the surfaces are covered by loose icy particles, produced by collisional resurfacing of EKOs. In Sect. 3 the total dust production rate over the entire Edgeworth-Kuiper Belt is calculated by using the same size distribution of EKOs modelled by Stern (1996). Our results are compared with the production rate of collisional debris predicted by Stern (1996) in Sect. 4. A summary of our results is presented in Sect. 5.

2. Model construction

We shall estimate the dust production rate of hypervelocity impacts on EKOs by interstellar dust. The surface condition of the target is an important parameter in the cratering process. Since the escape velocity of EKOs is small (less than about 10^4 cm s^{-1}), for hard icy surfaces the effect of material strength dominates over the effect of gravity in the cratering process. If the surface of an EKO is covered by a layer of icy particles (Luu & Jewitt 1996), however, the effect of gravity dominates the cratering process. Therefore, we shall estimate the dust production rate separately for both a hard surface and for a surface covered by icy particles.

2.1. Model for a hard surface of ice material

The first model assumes that EKOs have a hard surface of ice material. In previous works, impact experiments onto water ice targets were performed to investigate the crater volume (e.g., Lange & Ahrens 1987; Frisch 1992; Eichhorn & Grün 1993). Frisch (1992) used particles with masses 7.6×10^{-9}g to 2.5×10^{-6}g for the projectile, while Lange & Ahrens (1987) applied a particle mass of 8 g for the projectile. On the other hand, Eichhorn & Grün (1993) used smaller particles with masses between 10^{-14}g and 8×10^{-11}g as the projectiles. The data of Eichhorn & Grün (1993) is appropriate for the study of craters produced by the impacts of interstellar dust grains, which have an average mass of about 8×10^{-13}g (Grün et al. 1993). Eichhorn & Grün (1993) compared their results with those obtained by Frisch (1992) and Lange & Ahrens (1987), and gave an expression for the crater volume V_c [cm^3], as a function of the kinetic energy E_{kin} [eV] of the projectile, which holds over 10 orders of magnitude in kinetic energy:

$$V_c\rho = 2.34 \times 10^{-20} E_{kin}^{0.98} \times \rho, \quad (1)$$

$$E_{kin} = 0.5 m_i v_i^2 \quad (2)$$

where ρ [g cm^{-3}] is the density of the ice, and v_i [cm s^{-1}] and m_i [g] are the impact velocity and mean mass of interstellar dust grains respectively. We assume that the density of ice targets ρ is 1.0 g cm^{-3}, the mean particle mass of interstellar dust m_i is 8×10^{-13}g, and the impact velocity v_i is 26 km s^{-1} (Grün et al. 1993). Substituting these values into Eqs.(1)-(2), we obtain,

$$V_c\rho = 2.25 \times 10^{-8}[\mathrm{g}]. \quad (3)$$

Since the impact velocity is sufficiently high (26 km s^{-1}), the total mass of the ejecta is about four orders of magnitude higher than the mass of the impacting particle.

It should be noted that some of the excavated material may melt or vaporize. According to Melosh (1989), the ratio of the mass of melted material M_m to the mass of the projectile m_i is given by

$$M_m/m_i = 0.14 v_i^2/\epsilon_m, \quad (4)$$

where ϵ_m is the specific internal energy for melting the target material. Substituting $\epsilon_m = 2 \times 10^{10}$erg g^{-1} for an ice target (Melosh 1989) and $m_i = 8 \times 10^{-13}$g, we found $M_m = 3.8 \times 10^{-11}$g. Therefore, the mass of the melted material is about 0.2% of the total mass of excavated material. In addition, the former is always larger than the vapor mass by a factor of nearly 10 (Melosh 1989). Consequently, both the masses of the melted and vaporized material are negligibly small compared to the total mass of excavated material.

Impact ejecta with velocity smaller than the escape velocity of the target body would eventually fall back and deposit on the surface. The amount of escaping ejecta depends on the velocity distribution of excavated material and on the gravity of the target body. Unfortunately, the velocity distribution of icy ejecta has not yet been investigated in previous impact experiments onto icy targets. Therefore, the amount of ejecta escaping from the icy target bodies is estimated in the following way.

When the target is composed of hard materials, the effect of material strength dominates the cratering process; this is referred to as the strength regime (e.g., Housen et al. 1983). According to Housen et al. (1983), the volume $V_t(> v_e)$ of ejecta with velocity higher than v_e can be expressed in the strength regime by:

$$\frac{V_t(> v_e)}{R^3} = K_4 \left(v_e \sqrt{\frac{\rho}{Y}} \right)^{\frac{6\alpha}{\alpha - 3}} \quad (5)$$

where R is the crater radius, Y the target strength, K_4 a constant, and α is a parameter related to energy and momentum coupling in cratering events. By presenting the physical arguments for α, Holsapple & Schmidt (1982) restricted α to the range $3/7 \leq \alpha \leq 3/4$. Physically, when $\alpha = 3/4$, the projectile energy is important for the crater dimensions. On the other hand, when $\alpha = 3/7$, the projectile momentum is important (Holsapple & Schmidt 1982). From the results of impact experiments, Housen et al. (1983) reported $\alpha = 3/4$ for a basalt target, and 0.51 for a sand target. The cratering process in an ice target is expected to be similar to that for a basalt target rather than that for a loose sand target. Since the value of $\alpha = 3/4$ for a basalt target seems to be the theoretical upper limit of α, we assume that the value of α for an ice target is equal to or smaller than 3/4. When the target body has a larger mass (e.g., the Moon), the amount of escaping ejecta is very sensitive to the velocity distribution of the ejecta. In that case, the value of α is a key factor. But since the majority of EKOs have low escape velocities, the amount of escaping ejecta is not so sensitive to the value of α. Therefore in the following we adopt $\alpha = 3/4$ for impacts on hard icy surfaces.

Substituting $\alpha = 3/4$ into Eq.(5), we obtained,

$$\frac{V_t(> v_e)}{R^3} = K_4 \left(v_e \sqrt{\frac{\rho}{Y}} \right)^{-2}. \quad (6)$$

From the definition of $V_t(> v_{min}) = V_c$,

$$\frac{V_c}{R^3} = K_4 \left(v_{min} \sqrt{\frac{\rho}{Y}} \right)^{-2} \quad (7)$$

where v_{min} is the minimum velocity of the ejecta. From Eqs.(6) and (7), we obtained,

$$V_t(> v_e) = V_c \left(\frac{v_e}{v_{min}} \right)^{-2}. \quad (8)$$

Substituting Eq.(3) into Eq.(8), we obtained the total mass of ejecta with velocities higher than the escape velocity v_{esc} of target body, as

$$V_t(> v_{esc})\rho = 2.25 \times 10^{-8} \left(\frac{v_{esc}}{v_{min}} \right)^{-2}. \quad (9)$$

If we assume that the EKO with $\rho = 1$ g cm^{-3} has a spherical shape with radius s [cm], v_{esc} is presented by

$$v_{esc}[\text{cm s}^{-1}] = 7.48 \times 10^{-4} \times s. \quad (10)$$

From the observations by the Ulysses spacecraft, the flux of interstellar grains f is estimated to be 8×10^{-9}cm^{-2}s^{-1} (Grün et al. 1993). Using this value and Eqs.(9) & (10), we can calculate the mass flux of escaping ejecta $F_t(> v_{esc})$ produced by the impact of an interstellar dust particle,

$$\begin{aligned} F_t(> v_{esc}) &= V_t(> v_{esc})\rho f \\ &= 3.2 \times 10^{-10} \left(\frac{s}{v_{min}} \right)^{-2} [\text{ g s}^{-1}\text{cm}^{-2}]. \end{aligned} \quad (11)$$

We set minimum velocities ranging from 10 cm s^{-1} to 10^3 cm s^{-1} in Eq.(11). From impact experiments onto water ice targets, Frisch (1992) measured velocities of ice ejecta ranging from 4×10^2 cm s^{-1} to 5.7×10^4 cm s^{-1}. Due to the detection limit of the experimental setup, the real minimum velocity could be lower than 4×10^2 cm s^{-1}. Based on her laboratory measurements, Onose (1996) reported that the minimum velocity of ice ejecta was around tens of cm s^{-1}. Thus the minimum velocities ranging from 10 cm s^{-1} to 10^3 cm s^{-1} employed here seem to be reasonable for icy ejecta.

2.2. *Model for a layer of icy particles*

The second model assumes that the surfaces of EKOs are covered by a layer of icy particles. We note that if the size of the particles is sufficiently larger than that of the interstellar dust grain, the impact by the latter produces a crater on the surface of an individual particle. This process can then be treated as the hard surface case presented in Sect. 2.1. On the other hand, if the layer of particles is composed of fine grains which are smaller than the interstellar dust grains, an impact crater will be produced in the layer of the particles. This case shall be examined in the following.

Gravity dominates over material strength for cratering in a layer of particles; this is generally referred to as the gravity regime (Housen et al. 1983). Therefore the cratering process is not sufficiently affected by the properties of the target material. Hence we assume that the cratering process in icy particles is similar to that of sand targets.

Housen et al. (1983) formulated the distribution of velocity in the lower velocity ($\sim$ m s^{-1}) region of powdery ejecta, based on experiments of impact cratering on sand targets. Their result is expressed as,

$$\frac{V_t(> v_e)}{R^3} = 0.32 \left(\frac{v_e}{\sqrt{gR}} \right)^{-1.22} \quad (12)$$

where g is the surface gravity and R is the carter radius. On the other hand, the velocity distribution of powdery ejecta with velocities higher than several hundred m s^{-1} has been detected recently by Yamamoto & Nakamura (1997). Their data are fitted by the same scaling formula to give the following relation:

$$\frac{V_t(> v_e)}{R^3} = 0.03 \left(\frac{v_e}{\sqrt{gR}} \right)^{-1.2}. \quad (13)$$

In this study we estimate the impact ejecta from target bodies with radii ranging from hundreds of m to hundreds of km, with corresponding escape velocities from about tens of cm s^{-1} to hundreds of m s^{-1}. The reason why $V_t(> v_e)$ derived from Eq.(12) is about one order of magnitude higher than that derived from Eq.(13) is unclear. This difference affects the total mass estimation of ejecta escaping from the target body. Therefore, we use Eq.(12) and Eq.(13) separately to obtain the upper and lower estimates of the total dust production rate from the surface of icy particles.

According to Schmidt & Holsapple (1982), the crater radius R in particles targets is given by the following:

$$\Pi_r \Pi_2^{0.167} = 0.847 \ , \quad (14)$$

$$\Pi_r = R \left(\frac{\rho}{m_i} \right)^{1/3} \ , \ \Pi_2 = \frac{3.22 g r}{v_i^2},$$

where r is a radius of projectile. By using Eq.(10), the surface gravity is expressed as

$$g = \sqrt{G\rho \frac{2\pi}{3}} v_{esc} = 3.74 \times 10^{-4} v_{esc} \quad (15)$$

where G is the gravitational constant. Substituting Eq.(15), $r = (3m_i/4\pi\delta)^{1/3}$, and an impactor density of $\delta = 2.5$ g cm^{-3} (Grün et al. 1985) into Eq.(14), the crater radius in the particles target is:

$$R = 0.23 \times v_{esc}^{-0.167}. \quad (16)$$

We have assumed that the porosity of particles was 0.5 (Yen & Chaki 1992) and the bulk density was 0.5 g cm^{-3}. Substituting Eq.(16) into Eqs.(12) and (13), the total volume of ejecta escaping from the target body is derived. The upper estimate is

$$V_t(> v_{esc}) = 1.3 \times 10^{-5} \times v_{esc}^{-1.21}, \quad (17)$$

whilst the lower estimate is

$$V_t(> v_{esc}) = 1.3 \times 10^{-6} \times v_{esc}^{-1.20}. \quad (18)$$

Substituting Eq.(10) into Eqs.(17) and (18), and using the value of f for the flux of interstellar dust grains used in Eq.(11), we are able to calculate the mass flux of escaping ejecta by the impact of an interstellar dust grain. The upper estimate is

$$F_t(> v_{esc}) = 3.2 \times 10^{-10} s^{-1.21} [\mathrm{g\ s^{-1} cm^{-2}}] \quad (19)$$

whilst the lower estimate is

$$F_t(> v_{esc}) = 2.9 \times 10^{-11} s^{-1.20} [\mathrm{g\ s^{-1} cm^{-2}}] \quad (20)$$

In both cases we quote the power index to 3 significant figures.

3. Dust production rate by interstellar dust impacts

3.1. From one EKO

For impacts by interstellar dust, the cross section of an EKO is assumed simply as πs^2. The hard surface model leads to the production rate of dust escaping from one target as

$$F_t(> v_{esc}) \times \pi s^2 = 3.2 \times 10^{-10} \pi v_{min}^2. \quad (21)$$

Thus the dust production rate from an object with a hard surface is independent of the target size s, if we assume that the minimum velocity of the ejecta is independent of the target size (see Fig. 1). We note, however, that for small objects (i.e. $v_{min} > v_{esc}$), v_{esc} in Eq.(9) is replaced by v_{min}. As a result, the production rate of dust escaping from a small object becomes

$$V_t(> v_{min}) \rho f \times \pi s^2 = 1.8 \times 10^{-16} \pi s^2. \quad (22)$$

In the gravity regime, the crater volume in particles targets V_c is given by Schmidt & Holsapple (1982) as

$$\Pi_v \Pi_2^{0.506} = 0.234, \quad (23)$$
$$\Pi_v = \frac{V_c \rho}{m_i},$$

where Π_2 is defined in Eq.(14). From the definition of $V_t(> v_{min}) = V_c$ in Eq.(12), and from Eqs.(10), (14), (15) & (23), we obtained

$$\frac{v_{min}}{v_{esc}} \sim 0.52 s^{-0.58} \quad (24)$$

On the other hand, from Eqs.(13), (10), (14), (15) & (23),

$$\frac{v_{min}}{v_{esc}} \sim 0.07 s^{-0.58}. \quad (25)$$

If $s \geq 10^3$cm, $v_{min}/v_{esc} \ll 1$ in Eqs.(24) & (25). Therefore the escape velocity is always higher than v_{min}. This implies that the conditions which apply to Eq.(22) do not apply for a particles surface.

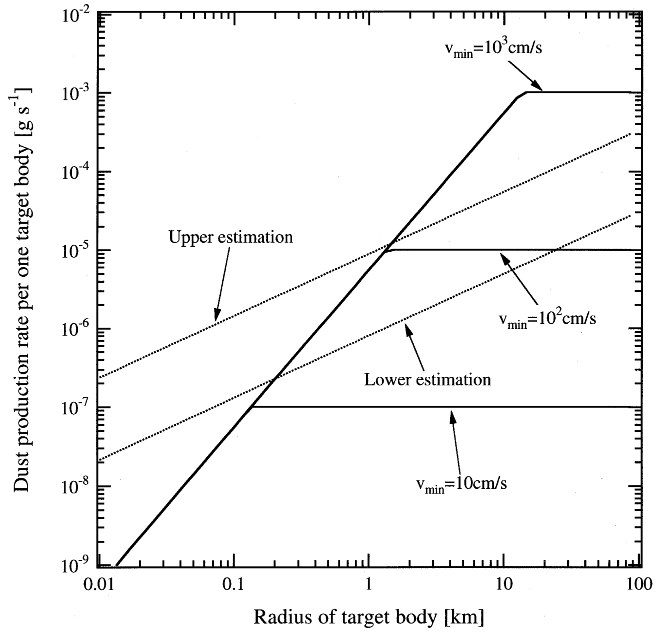

Fig. 1. The production rate of dust escaping from a target body with radii ranging from 10 m to 100 km, and covered by a hard icy surface (solid line), or by ice particles (dashed line).

Therefore, the production rate of dust escaping from one target body is derived from Eqs.(19) and (20) as

$$F_t(> v_{esc}) \times \pi s^2 = 3.2 \times 10^{-10} \pi s^{0.79}, \quad (26)$$

for the upper estimate, and

$$F_t(> v_{esc}) \times \pi s^2 = 2.9 \times 10^{-11} \pi s^{0.80}. \quad (27)$$

for the lower estimate.

These results demonstrate why the dust production rate in the case of icy particles surfaces depends on the target radius s for all target bodies, in contrast with the two different s-dependence dust production rates derived for the hard surface case (see Fig. 1).

3.2. From all EKOs

Next, we estimate the total dust production rate M_t by summing the ejecta mass from one target body, estimated in Sect. 3.1, over the entire Edgeworth-Kuiper Belt region. The size distribution of EKOs is a key factor. Stern (1995, 1996) investigated the rate of mutual collisions of EKOs with radii from 0.1 km to 162 km, and predicted a total production rate of collisional debris. Since it is worthwhile to compare the production rate by impacts of interstellar dust with that produced by mutual collisions of EKOs, we shall adopt the size distribution model of EKOs used by Stern (1995, 1996).

Stern's model assumes that EKOs obey a power law size distribution,

$$n(s)ds = N_0 s^{\beta} ds \quad (28)$$

where $n(s)ds$ is the number density of EKOs having radii between s and $s+ds$, and N_0 is a constant. Using the two models of EKO size distribution used in Stern (1995, 1996), we estimate the total dust production rate due to impacts by interstellar dust over all EKOs.

We note that the minimum size limit of EKOs is an important parameter in estimating the total dust production rates, both for dust production by EKOs mutual collisions and for that by impacts of interstellar dust on EKOs. Observations by the Hubble Space Telescope found 29 objects with radii ranging from 5 to 10 km in the Edgeworth-Kuiper Belt region (Cochran et al. 1995). Much smaller objects that are too faint to be detected, however, may exist in the Edgeworth-Kuiper Belt. Recent works on collisional evolution among EKOs assume the minimum radius of an EKO to be $\sim$ 0.1 km (Stern 1995, 1996; Davis & Farinella 1997). In order to make a comparison with the dust production rate by mutual collisions of EKOs predicted by Stern (1996), we also assume that the minimum radius of the object is 0.1 km. In addition, we adopt a maximum radius of 162 km, which is also the same value used by Stern (1996).

3.2.1. Nominal model

According to Jewitt & Luu (1995), there are about 3.5×10^4 QB_1 sized objects ($\geq$ 50 km in radius) in the Edgeworth-Kuiper Belt region. As a simple power-law with $\beta = -4.21$, the first model connects this population with about 10^{10} comets which Stern (1995, 1996) defined as bodies with radii between 1 and 6 km.

Note that Stern (1995, 1996) uses a power law with $\beta = -11/3$, and he defines the 3.5×10^4 QB_1 sized objects as bodies with radii $\geq$ 100 km, whereas Jewitt & Luu's (1995) estimate applies for radii $\geq$ 50 km. In this work we define the QB_1 sized objects as bodies with radii $\geq$ 50 km.

The normalization constant N_0 is calculated from the statistics of the 3.5×10^4 QB_1 sized objects by

$$\int_{5\times10^6}^{\infty} N_0 s^{-4.21} ds = 35000. \tag{29}$$

From Eq.(29), we obtained $N_0 = 3.6 \times 10^{26}$.

For the hard surface model, Eqs.(21) and (22) lead to

$$\begin{aligned} M_t &= \int_{10^4}^{\frac{v_{min}}{7.48\times10^{-4}}} 1.8 \times 10^{-16} \pi s^2 N_0 s^{-4.21} ds \\ &+ \int_{\frac{v_{min}}{7.48\times10^{-4}}}^{1.62\times10^7} 3.2 \times 10^{-10} \pi v_{min}^2 N_0 s^{-4.21} ds. \end{aligned} \tag{30}$$

Substituting v_{min}= 10 and 10^3 cm s^{-1} into Eq.(30), we find that the total dust production rate M_t ranges from 1.4×10^6 g s^{-1} to 2.4×10^6 g s^{-1}.

On the other hand, from Eqs.(26) and (27), the total production rate of dust from a surface of icy particles is

$$\begin{aligned} M_t &= \int_{10^4}^{1.62\times10^7} 3.2 \times 10^{-10} \pi s^{0.79} N_0 s^{-4.21} ds \\ &= 3.1 \times 10^7 \quad \text{[g s}^{-1}\text{] for the upper estimate,} \end{aligned} \tag{31}$$

and

$$\begin{aligned} M_t &= \int_{10^4}^{1.62\times10^7} 2.9 \times 10^{-11} \pi s^{0.80} N_0 s^{-4.21} ds \\ &= 3.1 \times 10^6 \quad \text{[g s}^{-1}\text{] for the lower estimate.} \end{aligned} \tag{32}$$

3.2.2. Constant mass model

The second model assumes a constant EKO mass distribution in every logarithmic size bin, and gives $\beta = -4$ (Stern 1995, 1996). Again, the normalization constant N_0 is calculated from the statistics of the 3.5×10^4 QB_1 sized objects (Jewitt & Luu 1995),

$$\int_{5\times10^6}^{\infty} N_0 s^{-4} ds = 35000 \tag{33}$$

giving $N_0 = 1.3 \times 10^{25}$. This model produces 4.3×10^9 comets with radii between 1 km and 6 km, and this result is consistent with the estimation by Duncan et al. (1995) that the total number of comets is roughly 5×10^9.

Following similar arguments as those for the nominal case described above, the total dust production rate for the hard surface model is,

$$\begin{aligned} M_t &= \int_{10^4}^{\frac{v_{min}}{7.48\times10^{-4}}} 1.8 \times 10^{-16} \pi s^2 N_0 s^{-4} ds \\ &+ \int_{\frac{v_{min}}{7.48\times10^{-4}}}^{1.62\times10^7} 3.2 \times 10^{-10} \pi v_{min}^2 N_0 s^{-4} ds. \end{aligned} \tag{34}$$

Substituting v_{min}= 10 and 10^3 cm s^{-1} into Eq.(34), we find that the total dust production rate is $M_t = 3.7 \times 10^5$ g s^{-1} and 7.3×10^5 g s^{-1} respectively.

For the case of icy particles surface model, we derive

$$\begin{aligned} M_t &= \int_{10^4}^{1.62\times10^7} 3.2 \times 10^{-10} \pi s^{0.79} N_0 s^{-4} ds \\ &= 8.5 \times 10^6 \quad \text{[g s}^{-1}\text{] for the upper estimate,} \end{aligned} \tag{35}$$

and

$$\begin{aligned} M_t &= \int_{10^4}^{1.62\times10^7} 2.9 \times 10^{-11} \pi s^{0.80} N_0 s^{-4} ds \\ &= 8.5 \times 10^5 \quad \text{[g s}^{-1}\text{] for the lower estimate.} \end{aligned} \tag{36}$$

3.3. Discussion

The total dust production rate M_t due to impacts by interstellar dust over the entire Edgeworth-Kuiper Belt is summarized in Table 1 for the cases considered.

The production rate of dust escaping from a larger object ($\geq$ 100 km) is about four orders of magnitude higher than that from a smaller object ($\sim$ 0.1 km) (see Fig. 1). On the other hand, the smaller objects are at least 7 orders of magnitude more

Table 1. Total dust production rate M_t due to impacts by interstellar dust over the entire Edgeworth-Kuiper Belt.

	Nominal model for the size distribution of EKOs	Constant mass model for the size distribution of EKOs
hard surface	$1.4 \times 10^6 \sim 2.4 \times 10^6$ [g s^{-1}]	$3.7 \times 10^5 \sim 7.3 \times 10^5$ [g s^{-1}]
	(v_{min} = $10 \sim 10^3$ cm s^{-1})	(v_{min} = $10 \sim 10^3$ cm s^{-1})
particles surface	$3.1 \times 10^6 \sim 3.1 \times 10^7$ [g s^{-1}]	$8.5 \times 10^5 \sim 8.5 \times 10^6$ [g s^{-1}]
	(depend on the velocity distribution of powdery ejecta)	(depend on the velocity distribution of powdery ejecta)

numerous than the larger target bodies from Eq.(28). Therefore, the major part of the dust produced in the Edgeworth-Kuiper Belt region originates from the smaller objects. In other words, the total dust production rate due to impacts by interstellar dust depends strongly on the number of small objects ($\leq$ 1km) in the Edgeworth-Kuiper Belt.

The minimum radius of an EKO was set at 0.1 km for comparison with the dust production rate by mutual collisions of EKOs (Stern 1996). However, much smaller objects that are too faint to be detected may exist in this region. Since most of the dust produced by impacts of interstellar dust comes from small objects, a reduction in the minimum radius of an EKO from 0.1 km to 10 or 1 m would lead to dust production rates higher than those estimated in this paper.

The sensitivity of our results to the value of α in Eq.(5) is tested. By using $\alpha = 3/7$, corresponding to the theoretical lower limit (Holsapple & Schmidt 1982), we re-derived the total dust production rate over all EKOs for the hard surface model. We find that the total dust production rates are 1.7×10^6g s^{-1} $\sim$ 2.4×10^6g s^{-1} for the nominal EKO's size distribution model, and 4.6×10^5g s^{-1} $\sim$ 7.3×10^5g s^{-1} for the constant mass model. These results are very similar to those derived for α = 3/4. Therefore we conclude that the assumption of $\alpha = 3/4$ for the ice targets does not have a significant influence on the total dust production rate, as long as $3/7 \leq \alpha \leq 3/4$.

Next, we estimate the optical depth of a dust cloud consisting of grains with the properties estimated in Table 1. The optical depth τ is defined by

$$\tau = \frac{M_t T_l}{4\pi a^3 \rho/3} \frac{\sigma l}{V_{belt}} \qquad (37)$$

where T_l is the lifetime of the grains, σ its cross section for extinction, l the width of the Edgeworth-Kuiper Belt, and V_{belt} the volume of the Edgeworth-Kuiper Belt region. For simplicity, we assume that all the grains have a radius $a = 10^{-4}$cm and hence $\sigma = \pi a^2 = 3.1 \times 10^{-8}$cm^2. Poynting-Robertson drag dominates the orbital evolution of grains with $a = 10^{-4}$cm in the Edgeworth-Kuiper Belt region (Liou et al. 1996) . Therefore, we take the timescale of the Poynting-Robertson drag T_{pr} as T_l, i.e.

$$T_{pr} = 7.0 \times 10^6 a \rho l_0^2 [\text{years}] \qquad (38)$$

where a and ρ are in CGS-units and l_0 is in AU (Wyatt & Whipple 1950). We further assume that the dust grains are in circular orbits at l_0 = 50AU. Substituting $a = 10^{-4}$cm, ρ = 1g cm^{-3} and l_0 = 50AU into Eq. (38), we obtain $T_{pr} = 5.5 \times 10^{13}$s. Assuming the Edgeworth-Kuiper Belt region is a band with thickness of 16deg around the ecliptic, with a width l = 20AU (Jewitt & Luu 1995), we calculated $V_{belt} = 1.9 \times 10^{44}$cm^3. Substituting these values into Eq. (37), τ is calculated to be 2.4×10^{-7} for $M_t = 3.7 \times 10^5$ g s^{-1}, and 2.0×10^{-5} for $M_t = 3.1 \times 10^7$g s^{-1}. Stern (1996) predicted the optical depth of debris produced by mutual collisions to be between 3×10^{-7} and 5×10^{-6}. Although our estimates are slightly higher than those predicted by Stern (1996), more detailed analysis of the optical properties of thin dust clouds is required to predict their detectability from the Earth.

4. Comparison with the dust production rate by mutual collisions of EKOs

Stern (1996) predicted a time-averaged production rate of debris between 9.5×10^8 and 3.2×10^{11}g s^{-1} due to the mutual collisions of EKOs, depending on the parameters used in his collisional simulations. In this section, we shall estimate the production rate of dust grains due to mutual collisions of EKOs, based on the prediction by Stern (1996), in the equivalent mass range used in our estimation.

From laboratory measurements of impact ejection, Gault et al.(1963) showed that the mass of the largest fragment is about 10% of the total ejected mass M_{te} for M_{te} ranging from 10^{-2}g to 10^2g. We extrapolated this relation to the crater produced by the impact of an interstellar dust grain. Namely, the impact of an interstellar dust grain excavates a small amount of target material and produces only ejecta with small sizes. For hard icy surfaces, we obtained a crater mass $V_c\rho = 2.25 \times 10^{-8}$g from Eq.(3). Such a crater mass suggests that the mass of the largest fragment is about 2.25×10^{-9}g, corresponding to a spherical dust grain with radius $a_m = 8\mu m$. Therefore we assume that the maximum radius of dust grains produced by impacts of interstellar dust is $10\mu m$. As noted before, in the case of a particles surface, the radius of the ejecta is smaller than that of the incident interstellar dust grains, i.e. $a_m \leq 1\mu m$.

On the other hand, the size of the collisional debris predicted by Stern (1996) ranges from multi-kilometer blocks to fine dust. In order to compare our results with his, it is necessary to estimate the fraction of dust grains with radii smaller than $10\mu m$ amongst the debris produced by mutual EKO collisions, as predicted by Stern (1996).

The size distribution of collisional debris was assumed by Stern (1996) to be $\sim a^{-3.5}$ in the range of radius a from 0.1 μm to 1 km. In this case, the total mass production rate of collisional debris is given by

$$\int_{10^{-5}}^{10^5} N_1 a^{-3.5} \frac{4\pi a^3 \rho}{3} da = M_{st}, \quad (39)$$

where M_{st} is $9.5 \times 10^8 \sim 3.2 \times 10^{11}$ g s^{-1} in Stern (1996). We found that the constant N_1 is $3.6 \times 10^5 \sim 1.2 \times 10^8$. Using this result, the production rate M_s of dust grains with radii between 0.1 μm and 10 μm can be given by

$$M_s = N_1 \times \int_{10^{-5}}^{10^{-3}} a^{-3.5} \frac{4\pi a^3 \rho}{3} da. \quad (40)$$

The value of M_s ranges from 8.6×10^4 g s^{-1} to 2.9×10^7 g s^{-1}, and is of about the same magnitude as that by impacts of interstellar dust given in Table 1.

We test the sensitivity of our result to the choice of a_m. Application of a_m=1μm decreases the range of M_s in Eq.(40) to the range 2.1×10^4 g s^{-1} $\sim 6.9 \times 10^6$ g s^{-1}, about 24% that for a_m=10μm. These production rates are still of the same order of magnitude as those we derived earlier. Furthermore, we tested the sensitivity of the results to the minimum dust radius of 0.1μm, and found that the minimum radius does not have a significant influence on the production rate M_s.

We note that the mutual collisions of debris made by the collisions between EKOs may play a significant role in the production of small dust grains. Since this scenario is rather complex and its examination is beyond the scope of this work, it will be studied at a later date.

5. Summary

We estimated the dust production rate by impacts of interstellar dust grains on EKOs. If EKOs have hard icy surfaces, and there are 10^{13} of these with radius $\geq$ 0.1km, we find that the total dust production rate over the entire Edgeworth-Kuiper Belt is between 3.7×10^5g s^{-1} and 2.4×10^6g s^{-1}, depending on the adopted minimum ejection velocity of 10 cm s^{-1} $\sim 10^3$ cm s^{-1}, and on the size distribution of the EKOs. On the other hand, if the surfaces of EKOs are covered by a layer of icy particles, the total dust production rate is 8.5×10^5g s^{-1} $\sim 3.1 \times 10^7$g s^{-1}. These results suggest that, in addition to mutual collisions of EKOs, impacts by interstellar dust are a significant source of interplanetary dust grains with radii less than about 10 μm, and which exist at large distances from the sun.

After leaving the Edgeworth-Kuiper Belt, the orbits of the dust grains evolve under the complex influences of the gravitational forces of the Sun and the giant planets, as well as solar radiation pressure and Poynting-Robertson drag forces. The mutual collisions of debris particles and the collisions by interstellar dust grains may also play important roles in the evolution of dust grains. Liou et al. (1996) showed that a grain with diameter larger than about 9μm is destroyed by the mutual collisions of debris and by the impact of interstellar dust before reaching the inner Solar System, whereas smaller grains can evolve towards the inner Solar System under Poynting-Robertson drag forces. The results of Liou et al. (1996) show that about 80% of the smaller grains produced in the Edgeworth-Kuiper Belt are ejected from the Solar System by the giant planets, while 20% of the grains enter the inner Solar System under the Poynting-Robertson drag forces. The maximum radius of the grains produced by the impact of interstellar dust is about 10μm as mentioned above. Thus, a fraction of the dust grains produced by the impact of interstellar dust on EKOs may contribute to the population of the interplanetary dust inside the orbit of Jupiter. However, the sublimation of icy particles should be taken into account when estimating the lifetime of the grains at such distances (Mukai 1986). Further investigations are required to understand the contribution of these grains to the interplanetary dust in the inner Solar System.

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