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Ice sublimation of dust particles and their detection in the outer solar system

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The flux of interplanetary dust beyond the Jupiter's orbit, which supposedly originates from Edgeworth-Kuiper belt, has been measured in situ by instruments on board Voyager and Pioneer spacecraft. The measured flux shows a nearly flat radial profile at 10–50 AU for Voyager and at 5–15 AU for Pioneer. Because the orbital evolution of dust particles controlled by radiation forces results in the flux that is inversely proportional to distance from the sun, dust particles detected by spacecraft should have suffered from other dynamical effects. We calculate model fluxes on the spacecraft taking into account the effect of ice sublimation as well as radiation forces on the orbital evolution of dust particles. Our results show that the radial profile of the model flux becomes relatively flat near the outer edge of the sublimation zone, where ice substantially sublimes. The expected location of the flat radial profile, which depends on the detection threshold of instruments, is 15–40 AU for Voyager and 5–20 AU for Pioneer. Because our model fluxes are comparable with the measured ones, we conclude that the flat radial profiles of the dust flux derived from in-situ dust impacts may be caused by ice sublimation.

Key words: Ice sublimation, Edgeworth-Kuiper belt, solar system, dust.

1. Introduction

Edgeworth-Kuiper belt objects are the least processed icy bodies that are located in the Edgeworth-Kuiper belt (EKB) currently at 30–50 AU from the sun. These objects (hereafter EKBOs) with sizes larger than 100 km have been observed by currently available telescopes, while smaller EKBOs are subjected to the detection limits of the telescopes. Although there is no report on the direct detection of EKBO-like bodies in orbit around other stars, observations of circumstellar debris disks suggest the presence of EKBO-like bodies producing dust particles in the disks (e.g., Artymowicz, 1997). EKBOs are thought to produce dust particles through mutual collisions between EKBOs and/or erosion of EKBO surfaces by impacts of interstellar dust streaming into the solar system (Stern, 1996; Yamamoto and Mukai, 1998). Theoretical studies indicate that timescales for dust particles released from EKBOs to drift inward by the Poynting-Robertson (P-R) effect are shorter than their timescales against collisional destruction in the outer solar system if their radii are smaller than $\sim 10\,\mu$m (Liou *et al.*, 1996). Therefore, EKB dust particles in orbit around the sun must drift inward by the P-R effect. While they are expected to spread out across the solar system, neither solar radiation scattered by EKB dust particles nor thermal radiation emitted from them has been detected to date. Contrary to those remote observations, instruments on board spacecraft have identified impacts of dust particles on the spacecraft beyond the Jupiter's orbit (Humes, 1980; Gurnett *et al.*, 1997). The major source of these dust particles detected in the outer solar system is most likely EKBOs, because no other sources are available there.

In-situ data on the flux of dust particles in the outer solar system put constraints on the dynamical evolution and production rate of the particles. Furthermore, these constraints would give new insights into the physical properties of EKB dust particles and the collisional processing of EKBO surfaces. Pioneer 10/11 measured a flux of 10^{-10}–10^{-9} cm^{-2} s^{-1} at 1–20 AU through pressurized cells whose pressure loss indicate dust impacts (Humes, 1980). Voyager 1/2 detected dust particles with a much higher flux of 10^{-8}–10^{-7} cm^{-2} s^{-1} at 10–50 AU through abrupt changes of voltage detected by antenna elements (Gurnett *et al.*, 1997). We expect the difference of the fluxes measured by these spacecraft may be explained by the size distribution of dust particles drifting from the EKB because the spacecraft have different detection size threshold. It turned out that the radial profiles of the fluxes are nearly flat at 10–50 AU for Voyager 1/2 and 5–15 AU for Pioneer 10/11. In contrast, the flux of dust particles controlled by radiation forces is inversely proportional to the heliocentric distance. Therefore, the flat profile implies that dust particles are affected by other dynamical effects.

It is natural to expect that EKB dust particles are mainly

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composed of ices together with refractory carbonaceous materials. If such icy dust particles drift inward by the P-R effect, the ice component in the particles intensively sublimes when their temperatures become about 100 K (Kobayashi *et al.*, 2008). Small icy dust particles of micrometer sizes actively sublime at 20–40 AU, while large dust particles sublime at smaller distances. This size-dependence comes from the fact that smaller dust particles have higher temperatures in the dust sizes ($\gtrsim 1\,\mu$m) we concern, owing to their lower emissivity. The locations of flat profiles in the measured fluxes may be explained by the difference in the size threshold of the instruments, because the locations coincide with heliocentric distances where dust particles of the threshold size actively sublime. When ice sublimes, some dust particles become smaller than the threshold of dust detection by the spacecraft, resulting in a decrease in the number of dust particles measured by the spacecraft. However, refractory grains encased in icy materials would sustain the detection to some extent in the ice sublimation zone as long as they drift inward by the P-R effect. This chain of events would prevents increasing fluxes with decreasing distance, which may form a relatively flat profile in the radial distribution of the flux. We propose ice sublimation to explain the flat profile in the fluxes measured by Pioneer and Voyager spacecraft.

In this paper, we investigate the effect of ice sublimation on the measured dust flux by considering the radiation pressure, the P-R drag, and ice sublimation. In Section 2, we describe our calculation model. The model fluxes on the spacecraft along with the in-situ data from Voyager 1/2 and Pioneer 10/11 are shown in Section 3. In Section 4, we discuss the masses produced in EKB, the gravitational effect of Jupiter and Saturn, and the sizes of refractory particles included in icy dust particles.

2. Model

We assume that dust particles produced in EKB have spherical shape and a power-law size distribution with the power index $-p$ in the radius range from $s_{\min}$ to $s_{\max}$. Each spherical particle consists of a pure H_2O ice mantle and an organic refractory core. We use the physical and optical properties for H_2O ice and organic refractory that are adopted in Kobayashi *et al.* (2008). The radius of the core, s_c, is given by $\gamma^{1/3}s$ where γ is the volume fraction of the refractory core in a spherical particle and s is the overall radius of the particle. Each particle does not necessarily have the same γ value. We assume that γ has a Gaussian distribution with its mean of 0.5 and the standard deviation of 0.1. The minimum radius $s_{\min}$ of dust particles in bound orbits is determined by the condition $\beta \leq 0.5$, for which we obtain $s_{\min} = 1.1\,\mu$m. Here β is the ratio of radiation pressure to solar gravity acting on a particle. Yamamoto and Mukai (1998) estimated the maximum radius $s_{\max} \sim 10\,\mu$m for EKB particles produced by the flux of interstellar dust assuming the average mass of 8×10^{-13} g. Because large interstellar dust of $> 8 \times 10^{-13}$ g should produce larger EKB particles, we set $s_{\max} = 20\,\mu$m.

EKB dust particles orbiting the sun gradually drift inward by the P-R effect with their drift velocity $\dot{a}$ proportional to β. When the temperatures of the particles exceed 100 K, the ice component of the particles starts to sublimate and their inward drifts almost stop at their sublimation zones because of an increase in β (Kobayashi *et al.*, 2008). After complete sublimation of the ice component, the remnant particles consisting only of the refractory component resume to drift inward by the P-R effect.

The dust flux $F(r, s_t)$ at a heliocentric distance of r measured by an instrument with its threshold of radius s_t is given by

$$F(r, s_t) = \frac{N_s(s_t, r)}{2kr\bar{i}} v_r, \tag{1}$$

where $N_s(s_t, r)$ is the surface number density of EKB dust particles with radii larger than s_t, $v_r = 20\,\mathrm{km\,s^{-1}}$ is the relative velocity between the spacecraft and the particles, $\bar{i}$ is the average inclination of the particles, $k = 1$ (Grün *et al.*, 1985). Because inclinations of dust particles are conserved during the orbital evolution under the P-R effect, $\bar{i}$ is identical to the average inclination of EKBOs, namely, $\bar{i} \sim 0.1$ (e.g., Noll *et al.*, 2008). The threshold for Voyager 1/2 is $s_t = 1.2\,\mu$m, and the threshold for Pioneer 10/11 $s_t = 4.5\,\mu$m and $s_t = 8.7\,\mu$m, respectively, assuming a mass density of $\rho = 1.4\,\mathrm{g\,cm^{-3}}$ for all particles.

We numerically calculate the surface number density $N_s(s_t, r)$ of EKB dust particles based on the method described in Kobayashi *et al.* (2008). We set $a_0 = 50$ AU and $e_0 = 10^{-4}$ where a_0 and e_0 are the initial semimajor axis and eccentricity of dust particles starting their inward drift by the P-R drag. As we will discuss later, the assumption of low eccentricities does not change our conclusions. At the outermost region $r_{\mathrm{out}} = a_0$, the surface number density $N_s(s_t, r_{\mathrm{out}})$ is given by

$$N_s(s_t, r_{\mathrm{out}}) = \frac{3\dot{M}_{\mathrm{dust}}}{8\pi^2 \rho\, r_{\mathrm{out}}} \int_{s_t}^{s_{\max}} \frac{s^{-p}}{\dot{a}} ds \left(\int_{s_{\min}}^{s_{\max}} s^{3-p} ds \right)^{-1}, \tag{2}$$

where $\dot{M}_{\mathrm{dust}}$ is the dust production rate in EKB and $\dot{a}$ is determined by the P-R effect at r_{out} for the particles having radius s. Here the dust production rate in the radius range $[s, s + ds]$ is proportional to $s^{-p}ds$. Note that the number density of drifting dust particles with radii in the range of $[s, s + ds]$ is proportional to s^{-p+1} if $\dot{a} \propto s^{-1}$ and sublimation is neglected (e.g., Moro-Martín and Malhotra, 2003). In this case, $F(r, s_t)$ is proportional to s_t^{2-p}, which may give the difference of magnitude of the measured flux by Voyager 1/2 from that by Pioneer 10/11.

3. Results

Figure 1 shows our model flux of EKB dust particles averaged out over γ in comparison with the measured fluxes. If ice sublimation is negligible, the surface number density is constant with heliocentric distance r. Thus the model flux $F(r, s_t)$ is inversely proportional to the heliocentric distance (see Eq. (1)). Because of the increase in β due to ice sublimation, radiation pressure on icy dust particles prevents their inward drift due to the P-R drag, resulting in a pile-up of the particles. The locations of the pile-up becomes further from the sun with γ. Although the surface number density increases by the pile-up, the sharpness of the

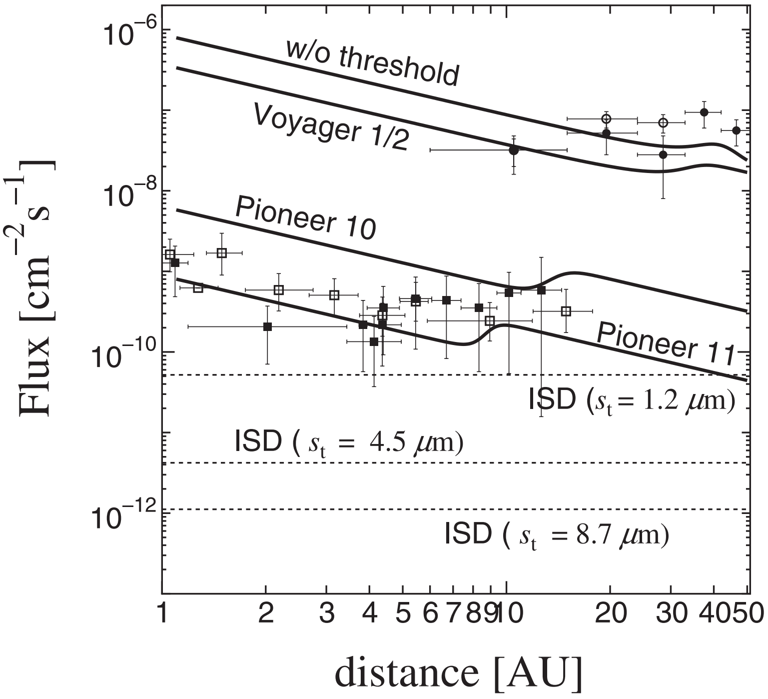

Fig. 1. Comparison of the model fluxes with threshold of Voyager 1/2 ($s_t = 1.2\,\mu$m), Pioneer 10 ($s_t = 4.5\,\mu$m), and Pioneer 11 ($s_t = 8.7\,\mu$m) with the fluxes measured by Voyager 1 (filled circle) and 2 (open circle) and Pioneer 10 (filled square) and 11 (open square). The solid line labeled "w/o threshold" shows the model flux without the threshold. The dotted lines show the flux of interstellar dust for the threshold of the above spacecraft.

pile-up is diluted by the average with γ. Furthermore, only a thin ice mantle sublimes and thus sublimation does not last long. Therefore, the enhancement of the surface number density is only a small factor of 1.4. The model flux is enhanced compared to that inversely proportional to the heliocentric distance. The slight enhancement is seen as a hump around 40 AU in the model flux if the size threshold is absent. As we will discuss later, the enhancement factor decreases with initial eccentricities of the particles. However, the pile-up occurs only for small particles because their β is large (Kobayashi *et al.*, 2009). Therefore, the effect of the pile-up is not seen in a model flux with the size threshold of several micrometers.

The number of dust particles larger than the threshold decreases during ice sublimation. This makes the surface number density lower than that expected without sublimation. Therefore, the flux is reduced around the outer edge of sublimation zone compared to that inversely proportional to the heliocentric distance. The reduction forms a bump in the model flux with the threshold of Voyagers 1/2 around 30–40 AU, while a similar bump appears around 10 AU for the threshold of Pioneer 10/11. The difference in the location of bump is explained by the difference in the threshold radius. The bumps are formed around the locations where dust particles with the threshold radius sublime substantially because small particles are the dominant population. While active sublimation at 100–110 K is independent of dust sizes, small dust sublimes prior to large dust because the temperature of small dust is higher (Kobayashi *et al.*, 2008). Therefore, the heliocentric distance of a bump of the model flux with Voyager's threshold ($s_t = 1.2\,\mu$m) is farther away from that with Pioneer's threshold ($s_t = 4.5\,\mu$m and $8.7\,\mu$m). The flux inside 30 AU with the threshold of Voyager and inside 8 AU with Pioneer 10/11 is mainly composed by refractory dust. In the region where only refractory components remain, the flux of the particles expected for all the spacecraft is inversely proportional to the heliocentric distance.

Our results with $\dot{M}_{\rm dust} = 1 \times 10^6\,\mathrm{g\,s^{-1}}$ and $p = 5$ show that the expected fluxes for Voyagers 1/2 are 2–3 orders of magnitude higher than those for Pioneer 10/11. Consequently, our model flux qualitatively agrees with in-situ measurements of dust particles in the outer solar system. Also plotted as dotted lines is the flux of interstellar dust derived from analysis of impact data by the dust counter on board Ulysses (Kimura *et al.*, 2003). The flux of dust particles measured by Voyager 1/2 and Pioneer 10/11 exceeds the interstellar dust flux.

4. Discussion

We have used $\dot{M}_{\rm dust} = 1 \times 10^6\,\mathrm{g\,s^{-1}}$ and $p = 5$ for the model flux to fit the measured fluxes for both Voyager and Pioneer by eye, as shown in Fig. 1. On the one hand, Yamamoto and Mukai (1998) estimated the mass production rate by impacts of interstellar dust onto EKBOs to be $\dot{M}_{\rm dust} = 3 \times 10^5$–$3 \times 10^7\,\mathrm{g\,s^{-1}}$. On the other hand, the dust production rate of dust particles with radii smaller than $20\,\mu$m by mutual collisions between EKBOs has been estimated at $\dot{M}_{\rm dust} = 1 \times 10^5\,\mathrm{g\,s^{-1}}$–$4 \times 10^7\,\mathrm{g\,s^{-1}}$ by Yamamoto and Mukai (1998), adapting the collisional parameter used by Stern (1996). Therefore, their estimates of $\dot{M}_{\rm dust}$ are consistent with the value we adopted. For dust particles in a steady state of the collision cascade, $p = 3.5$ is expected for the power-law index, instead of $p = 5$ that we adopted (Dohnanyi, 1969; Tanaka *et al.*, 1996). The model flux with $p = 3.5$ is still comparable to the measured fluxes for Voyager's data provided $\dot{M}_{\rm dust} = 4 \times 10^6$ g s^{-1}[†]. On the contrary, the model flux with $p = 3.5$ becomes 7–8 times larger than the measured fluxes of Pioneer's data because large particles are relatively populous for $p = 3.5$. However, this discrepancy may be erased once we take into account the gravitational perturbation by Jupiter and Saturn. Gravitational forces of these planets scatter large dust particles whose timescales for the P-R effect are longer than their dynamical timescales against the gravitational scattering. Namely, the gravitational scattering is less significant for dust particles measured by Voyager 1/2, because Voyager's fluxes are dominated by smaller particles than those in Pioneer's fluxes. In addition, the gravitational scattering by Neptune is much smaller than those by Jupiter and Saturn. Because Voyager 1/2 mainly measured dust fluxes beyond Saturn's orbit, the effect of gravitational scattering on the flux measured by Voyager 1/2 may be much smaller than those by Pioneer 10/11. Although the ejection efficiency due to the gravitational scattering of Neptune is only 5%, that of Jupiter and Saturn is about 80% for dust with size as large as the Pioneer threshold (Liou *et al.*, 1996). The model flux with Pioneer threshold from 14 to 4 AU gradually decreases with decreasing distance (Landgraf *et al.*, 2002; Moro-Martín and Malhotra, 2003). Assuming that the model flux with Voyager threshold are reduced by 5% only for the gravitational scattering of Neptune and that those with Pioneer threshold are by 80% for the scattering of Jupiter and Saturn, the model fluxes reproduce the measured fluxes for $p = 3.5$–4. Therefore, we expect that the measured fluxes for Voyager and Pioneer are simultaneously reproduced under full consideration of radiation pressure, the P-R drag, ice sublimation, and gravitational forces of planets.

If dust particles drift inward only by the P-R effect, the flux of the particles is inversely proportional to the distance from the sun. On the contrary, the radial profiles of dust flux measured by instruments on board spacecraft are relatively flat at 10–50 AU for Voyager 1/2 and at 5–15 AU for Pioneer 10/11. This means that dust particles in these region must have suffered from other dynamical effect(s), one of which is possibly sublimation of their ice component. It is worthwhile noting that dust particles with radius $s_{\rm t}$ make the largest contribution to the flux. Dust particles of initially $s = s_{\rm t}$, however, become undetected during ice sublimation, since their sizes are reduced to $s < s_{\rm t}$. We expect the flux of dust particles measured by spacecraft to decrease in the sublimation zone owing to a lack of these particles with initial radius $s_{\rm t}$. Nevertheless, the presence of a refractory core in the particles does not necessarily result in a considerable reduction of their flux at the sublimation zone. In our model, the flux of EKB dust particles shows a bump around the outer edge of the sublimation zone. The smaller the threshold radius of detection is, the larger the heliocentric distance of a bump in the flux is. As we found, a bump in the model flux of dust particles appears at a heliocentric distance where a roughly constant flux of dust particles was measured. We conclude that the flat profile of the measured dust flux may be caused by ice sublimation of EKB dust particles.

The measured fluxes are expected to be mainly composed of refractory particles inside 30 AU for Voyager 1/2 and inside 5 AU for Pioneer 10/11. The dynamics of the refractory particles after complete sublimation of their ice component, in other words, the flux of the refractory particles inside the ice-sublimation zone is determined by their β ratios. The measured flux mainly composed of refractory particles give some constraints on γ and the number of refractory particles included in an icy particle because γ and the number determine β of refractory particles. If the refractory particles have $\beta \geq 1$ for low γ and/or a large number of refractory particles included in an icy particle, the flux decreases remarkably inside the ice sublimation zone and would be much lower than the measured flux. On the contrary, if each icy dust particle contains a number of refractory particles with $\beta < 0.5$, the flux increases significantly in the sublimation zone and would be much higher than the measured flux. Our assumption of one refractory particle per each icy dust particle with $\gamma \sim 0.5$ would be appropriate because our model fluxes of refractory particles are consistent with the measured fluxes.

We have assumed a low initial eccentricity ($=10^{-4}$) of dust particles drifting from the EKB. Dust particles released from their parent bodies have eccentricities as large as β because the radiation pressure force per unit mass for the particles is much stronger than that for their parent bodies. A pile-up of dust particles hardly occurs if the particles drifting the sublimation zone have eccentricities larger than 0.1 (Kobayashi *et al.*, 2008, 2009). In contrast, the locations and sizes of bumps formed by ice sublimation are independent of initial eccentricities of dust particles because active ice sublimation is only induced by temperature $\simeq$100 K. Note that the bumps are only seen in the model fluxes if the detection threshold is taken into account (Fig. 1). Therefore, the assumption of the low initial eccentricity does not significantly affect the radial feature of model fluxes.

We have shown that the fluxes derived from in-situ data of Voyager and Pioneer are much higher than the flux of interstellar dust. This contrasts with the result by Mann and Kimura (2000), in which the interstellar dust flux measured by Ulysses is shown to agree with the Pioneer data. However, the interstellar dust flux adopted in Mann and Kimura (2000) is the average over heliocentric distances of 1–5 AU. The flux inside 2 AU is enhanced by the gravitational focusing by the sun. The interstellar dust flux adopted in Mann and Kimura (2000) is, therefore, overestimated beyond 2 AU and thus the agreement is just coincidence.

Future space missions will hopefully confirm that EKBOs are the dominant source of dust particles in the outer solar system. This is actually anticipated by the fact that Voyager did not detect dust particles beyond the outer edge of EKB (Gurnett *et al.*, 1997). New in-situ data for the dust flux in the outer solar system will be available from the New Horizons Mission. The Student Dust Counter (SDC) on board New Horizons has the threshold radius of

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[†] The mass production rate $\dot{M}_{\rm dust} = 4 \times 10^6$ g s^{-1} is estimated for $s_{\rm max} = 20\,\mu$m, which we adopt because the maximum size of dust particles produced by the erosion of impact with interstellar dust is of the order of 10 μm (Yamamoto and Mukai, 1998). If we adopt $s_{\rm max} \simeq 200\,\mu$m, we obtain $\dot{M}_{\rm dust} \sim 10^7$ g s^{-1}, which is consistent with Landgraf *et al.* (2002) and Moro-Martín and Malhotra (2003).

$s_t = 0.8\,\mu$m (Horányi *et al.*, 2007). With this threshold ($s_t < s_{\rm min}$), we estimate the flux measured by SDC to be $3 \times 10^{-8}\,{\rm cm}^{-2}\,{\rm s}^{-1}$ in the EKB region. In addition, SDC might detect an enhancement of the flux at 30–40 AU as a result of ice sublimation from the smallest icy particles. If such an enhancement is observed, the enhanced flux reveals the inner structure of icy dust particles. We expect that our model will be tested by New Horizons.

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