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Thermal radiation from dust grains in Edgeworth-Kuiper Belt

S. Yamamoto and T. Mukai

The Graduate School of Science and Technology, Kobe University, Nada, Kobe 657-8501, Japan

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We calculate the temperature of dust grains produced in Edgeworth-Kuiper Belt (EKB) based on the grain model for water-ice and silicate mixtures. The dust grains with radii ranging from 0.1 μm to 1 mm have low temperatures of about 20 K to 50 K in EKB, depending on their size, solar distance, and a volume mixing ratio of silicate to water-ice. We also estimate the thermal radiation from dust cloud in EKB. The result of thermal emission shows the spectral feature of water-ice at the wavelength of about 60 μm. Although it is difficult to estimate the possibility to detect the thermal emission spectrum of EKB dust cloud, due to large uncertainties in its spatial density, we found that the thermal emission of dust cloud in EKB lies below the IRAS data of foreground zodiacal emission. The maximum value of the thermal emission derived from the acceptable dust cloud model in EKB, however, becomes to be comparable to that of foreground zodiacal emission in far-infrared and submillimeter wavelength domains. Since the EKB dust cloud seems to concentrate near the ecliptic plane, a scanning of infrared observation along a line perpendicular to the ecliptic plane may reveal the presence of such dust cloud in the future.

1. Introduction

Recently, it has been suggested that significant dust production occurs in Edgeworth-Kuiper Belt (EKB) (e.g., Backman *et al.*, 1995; Liou *et al.*, 1996; Stern, 1996; Yamamoto and Mukai, 1998). One mechanism to produce dust is the mutual collisions of Edgeworth-Kuiper Belt objects (EKOs) (Backman *et al.*, 1995; Stern, 1995, 1996), and another is the interstellar dust impacts on EKOs (Yamamoto and Mukai, 1998). However, the existence of these dust grains produced in EKB region has not been directly confirmed by observations of zodiacal light/emission and *in situ* measurements.

Backman *et al.* (1995) and Stern (1996) calculated the thermal emission brightness from debris created by the mutual collisions of EKOs. Backman *et al.* (1995) investigated the detectability of the emission by COBE. Stern (1996) reported that the thermal emission brightness exceeds the detection limits of ISO and SITRF, while that is most likely below IRAS detection limits.

The thermal emission brightness depends strongly on the temperature and the emission/absorption efficiency of dust grains. In order to estimate these grain's nature, an optical property of grain becomes important. In the previous works, the simple models of an optical property of grain were used due to the lack of specific knowledge about grain properties. Backman *et al.* (1995) used a simple model for grain emissivities and albedo. Stern (1996) used the representative temperature of 40 K to 60 K for EKB dust cloud.

It has been considered that EKB region is a comet reservoir extending outside the orbit of Neptune. Cochran *et al.* (1995) detected comet-sized objects in EKB using Hubble Space Telescope. Thus, the dust grain from EKO has icy material including small refractory particles such as cometary dust. In order to estimate the thermal radiation from EKB dust cloud, it is important to take into account the optical properties of such a grain.

In this study, we will estimate the temperature of EKB dust grains based on the grain model for water-ice and silicate mixtures such as cometary dust, using the optical constants deduced from the Maxwell-Garnett mixing rule (e.g., Mukai, 1986). From the results, we reexamine the thermal emission from EKB dust cloud, and investigate the detectability of thermal radiation from EKB dust cloud produced by the mutual collisions of EKOs and by the interstellar dust impacts on EKOs, taking into account the contribution of foreground thermal emission.

2. Temperature of EKB Dust Grain

In this section, we examine the temperature of dust grains produced in EKB, based on the model of heterogeneous icy material including small refractory particles (Mukai, 1986).

A grain absorbs the solar energy of E_a and simultaneously emits the energy of E_r. These energy sources are defined by

$$E_a = \pi (R_\odot / r)^2 \int_0^\infty \pi a^2 B_\odot(\lambda) Q_{\mathrm{abs}}(a, \lambda, m^*) d\lambda, \quad (1)$$

$$E_r = 4\pi \int_0^\infty \pi a^2 B(\lambda, T_g) Q_{\mathrm{abs}}(a, \lambda, m^*) d\lambda, \quad (2)$$

where λ is a wavelength, $R_\odot$ and $B_\odot(\lambda)$ are the radius and solar surface brightness, respectively, and r is the solar distance of dust grain with a radius of a. The Planck function $B(\lambda, T_g)$ at the temperature T_g of the dust grain is defined by $B(\lambda, T_g) = 2hc^2\lambda^{-5}[\exp(hc/\lambda k_b T_g) - 1]^{-1}$, where h, k_b, and c are the Planck constant, the Boltzmann constant, and the speed of light, respectively. For simplicity we assume that the dust grain from EKO has a spherical shape. In this case, the efficiency factor for absorption/emission Q_{abs} is deduced

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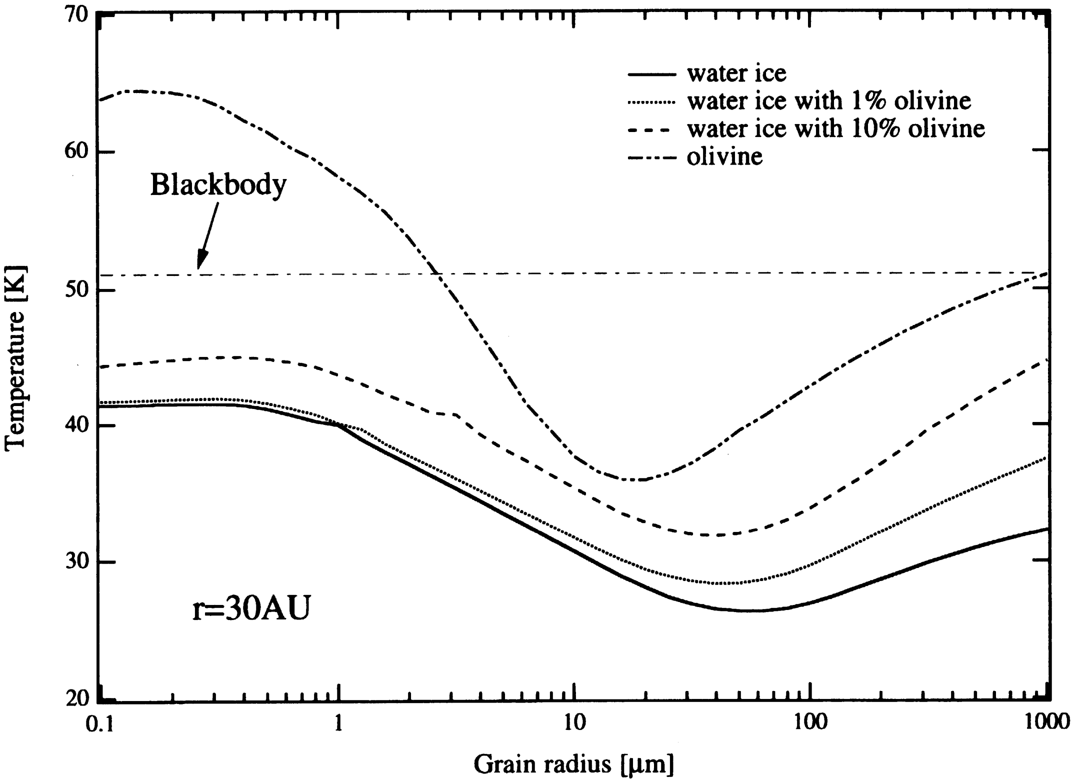

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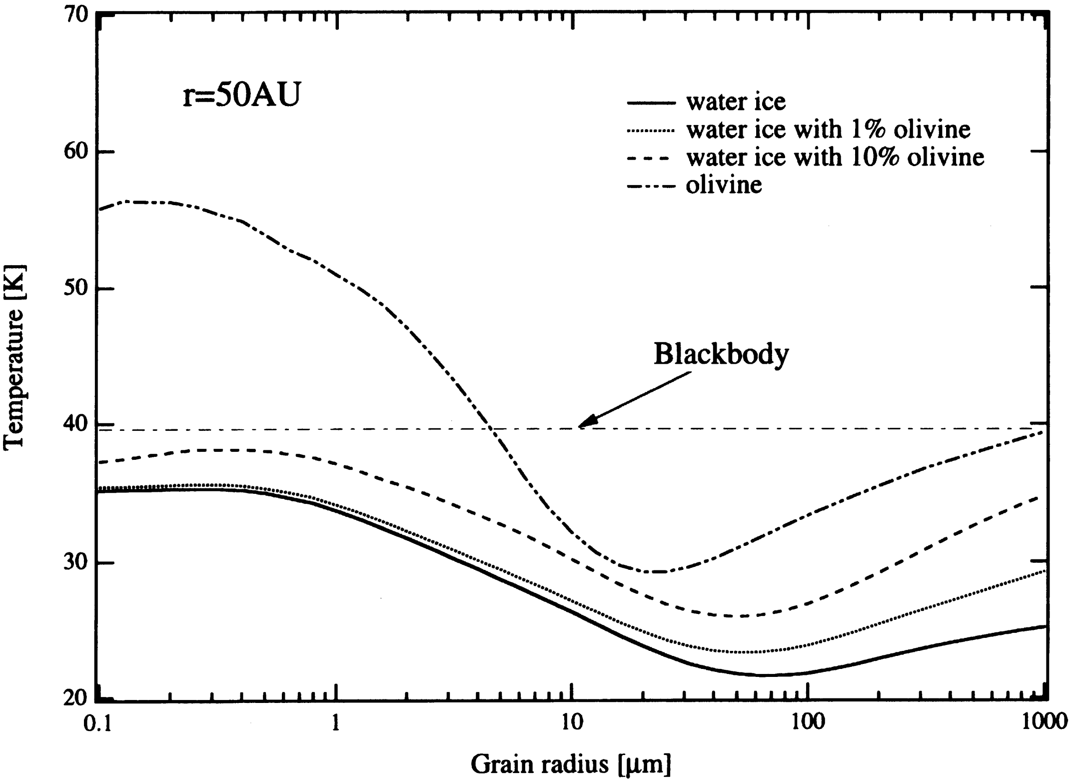


(b)

Fig. 1. Temperature of the grain, consisting of icy matrix with olivine inclusions, at a solar distance of (a) $r = 30$ AU and (b) $r = 50$ AU. A volume fraction of olivine is 0%, 1%, and 10%. Dash-dotted line indicates the blackbody temperature.

by Mie Theory as functions of a, λ and m^*, where m^* is the complex refractive index of grain material. For the case of heterogeneous icy material consisting of icy matrix embedded with small refractory inclusions, the Maxwell-Garnett mixing rule to calculate m^* is applicable (Mukai, 1986).

We used the dielectric function of olivine for inclusions and water-ice for the matrix. For the optical constants of water-ice, we employ the data of Warren (1984) in a domain of wavelength $\lambda = 0.14$–$1000\ \mu$m. For olivine, we used the data given by Huffman and Stapp (1973) and Huffman (1976) in $\lambda = 0.14$–$7\ \mu$m, and those by Mukai and Koike (1990) in $\lambda = 7$–$200\ \mu$m. Since no data of the optical constant for olivine beyond $\lambda = 200\ \mu$m are available, the constant value of m^* of Mukai and Koike (1990) at $\lambda = 200\ \mu$m is used in $\lambda = 200$–$1000\ \mu$m for olivine. This assumption does not have a significant influence on the result. The solar spectrum of $B_\odot$ is complied in Mukai (1990) in $\lambda = 0.14$–$300\ \mu$m wavelength domain. For the $B_\odot$ beyond $\lambda = 300\ \mu$m to $1000\ \mu$m, we adopted the brightness temperature of 5780 K.

The integration of Eqs. (1) and (2) is carried out in the wavelength domain of $0.14\ \mu$m to $1000\ \mu$m. Under a local thermal equilibrium of the grain, the input energy on the grain is balanced with the output energy, i.e., $E_a = E_r$. The energy loss by sublimation of water-ice is negligibly small in the region of interest. Consequently, we obtained the equilibrium temperature of EKB dust grain as functions of a and r.

The resulting temperatures for the volume fraction of olivine of 0%, 1%, and 10% are plotted in Fig. 1. As increasing the volume fraction of olivine, the temperature of grain increases compared with that of pure water-ice. According to Greenberg (1982), the expected volume faction of refractory materials in cometary dust is less than 10%. In this case, the temperature of dust grain in EKB seems to be lower than that of blackbody (Fig. 1). Furthermore, we calculated the temperature for the case of higher refractory material (100%), that is a pure olivine grain. While the temperature of grains with radii less than a few μm becomes to be higher than the blackbody temperature, the grains with radii larger than a few μm still have lower temperature compared to the blackbody temperature (Fig. 1).

Backman *et al.* (1995) calculated that the small grain with radius of $1\ \mu$m would have a temperature of 100 K and the larger grain would have a temperature of about 40 K at 30 AU, based on a simple model for grain emissivities and albedo. Stern (1996) used the isothermal model of temperature at 40 K to 60 K, which values were estimated from those of the blackbody in EKB region. On the contrary, we found that the dust grain in EKB has temperature ranging from 20 K to 50 K, when EKB dust grain is heterogeneous icy material consisting of refractory inclusions embedded in the icy matrix, such as cometary dust.

3. Thermal Emission from EKB Dust Cloud

Based on the results of EKB dust temperature $T_g(a, r)$ obtained above, we will estimate the thermal emission from EKB dust cloud. The thermal emission of EKB dust cloud $B_{\mathrm{EKO}}(\lambda)d\lambda$ within the range of wavelength λ to $\lambda + d\lambda$ is calculated as

$$B_{\mathrm{EKO}}(\lambda) = \int_{\theta(r=30\ \mathrm{AU})}^{\theta(r=50\ \mathrm{AU})} \frac{\sin e}{\sin^2\theta} d\theta \cdot \int_{a_1}^{a_2} n(a,r)\pi a^2 Q_{\mathrm{abs}}(a,\lambda,m^*) \cdot B(\lambda, T_g(a,r))da, \quad (3)$$

where a_1 and a_2 are, respectively, the minimum radius and the maximum radius of EKB dust grain, r is a solar distance, e is an elongation angle (angle between the radial direction from the Earth to the Sun and the line of sight), and θ is an angle between the line of sight and the radial direction from the Sun to the EKB dust (see, Peterson, 1963). The width of EKB region is assumed to be from $r = 30$ AU to $r = 50$ AU (Jewitt and Luu, 1995).

For simplicity, the number density $n(a, r)da$ of EKB dust with radii between a and $a + da$ at the solar distance r is assumed as,

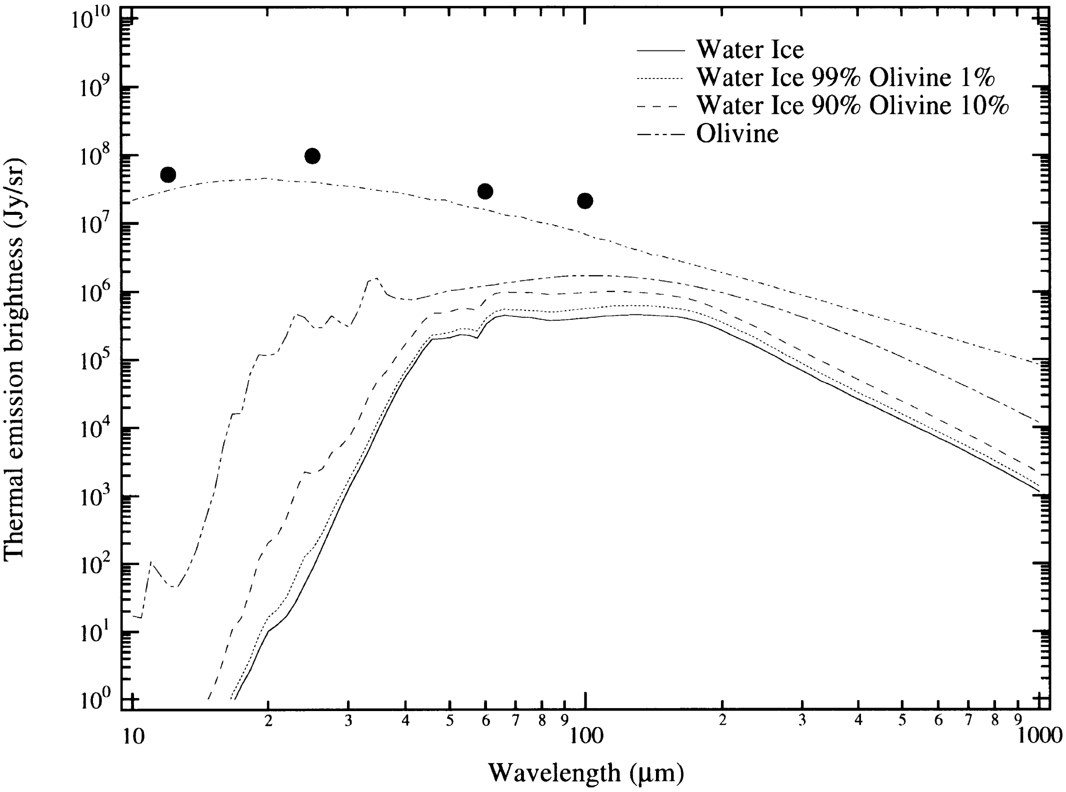
$$n(a,r)da = C_0 a^\beta (D/r)^q da, \quad (4)$$

where C_0 is a constant, a power-law exponent β is -3.5 (Backman *et al.*, 1995; Stern, 1996), $D = 30$ AU, and q is a power-law exponent. The value of q depends on the spatial distribution of dust grain in EKB. The dust grain in EKB evolves its orbit under the complex influences of gravitational forces of the Sun and the giant planets, mutual collisions of grains, as well as solar radiation pressure and Poynting-Robertson effects (Liou *et al.*, 1996). For simplicity, we assume a constant radial distribution of EKB dust, that is $q = 0$. In order to calculate $B_{\mathrm{EKO}}(\lambda)$ in Eq. (3), it is necessary to determine the value of C_0 in Eq. (4). According to Grün *et al.* (1985), the total cross-sectional area for the interplanetary meteoroids is estimated to be 4.6×10^{-21} cm^2/cm^3 at 1 AU. If the total cross-sectional area of EKB dust cloud is f times as large as that of interplanetary flux model at 1 AU, the value of C_0 is derived from Eq. (4),

$$C_0 \int_{r=30\ \mathrm{AU}}^{r=50\ \mathrm{AU}} (D/r)^q dr \int_{a_1}^{a_2} a^{-3.5}\pi a^2 da = f \times 4.6 \times 10^{-21} \times (50\ [\mathrm{AU}] - 30\ [\mathrm{AU}]). \quad (5)$$

Stern (1996) predicted that the optical depth of debris produced by mutual collisions of EKOs is between 3×10^{-7} to 5×10^{-6} for infrared wavelength domain. On the other hand, from IRAS observations, the optical depth of zodiacal emission at a wavelength of $12\ \mu$m in the ecliptic plane at elongation 91.1° was estimated to be 3×10^{-7} to 2.8×10^{-6} (Hauser *et al.*, 1984). Consequently, the ratio of optical depth of EKB dust cloud to that of interplanetary flux model is ranging from about 0.1 to 20. If we assume that the total cross-sectional area is proportional to the optical depth, the value of f is estimated to be about 0.1 to 20. Consequently, assuming $a_1 = 10^{-5}$ cm and $a_2 = 10^{-1}$ cm, the value of C_0 becomes 2×10^{-25} to 4×10^{-23} from Eq. (5).

On the other hand, Yamamoto and Mukai (1998) estimated that the optical depth of grains produced by interstellar dust impacts on EKOs is ranging from 2.4×10^{-7} to 2.0×10^{-5}. Again, we assume that the total cross-sectional area is proportional to the optical depth, and then the value of f is



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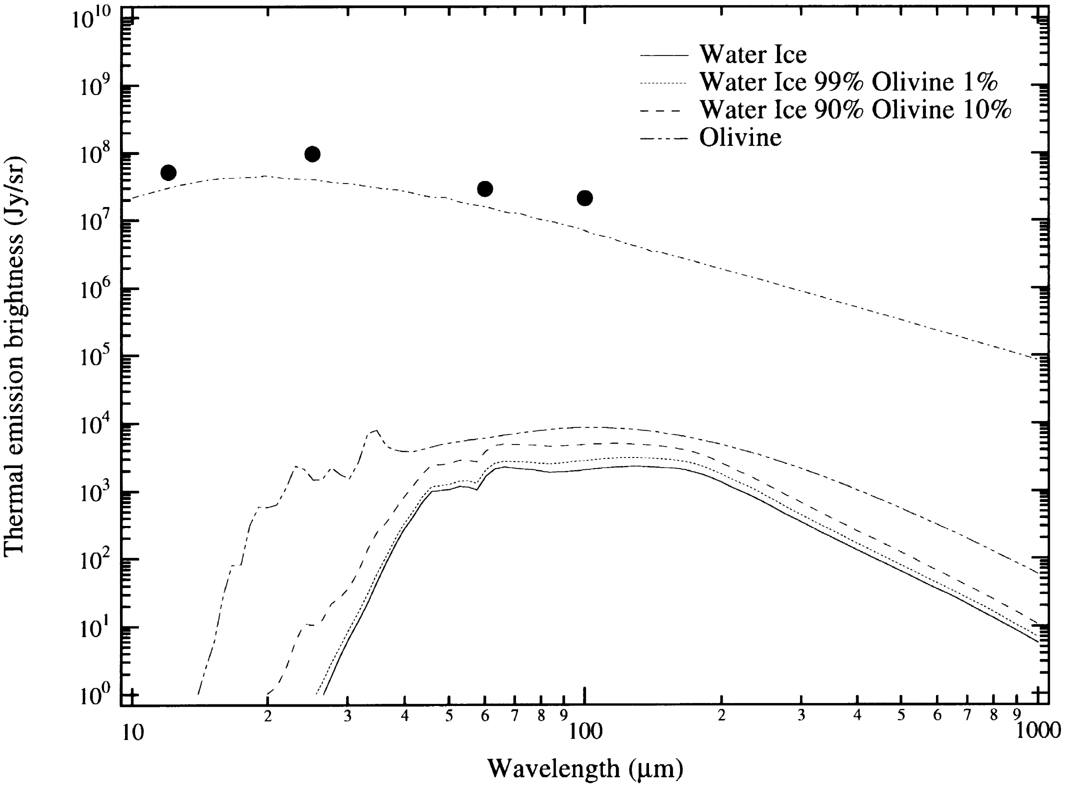
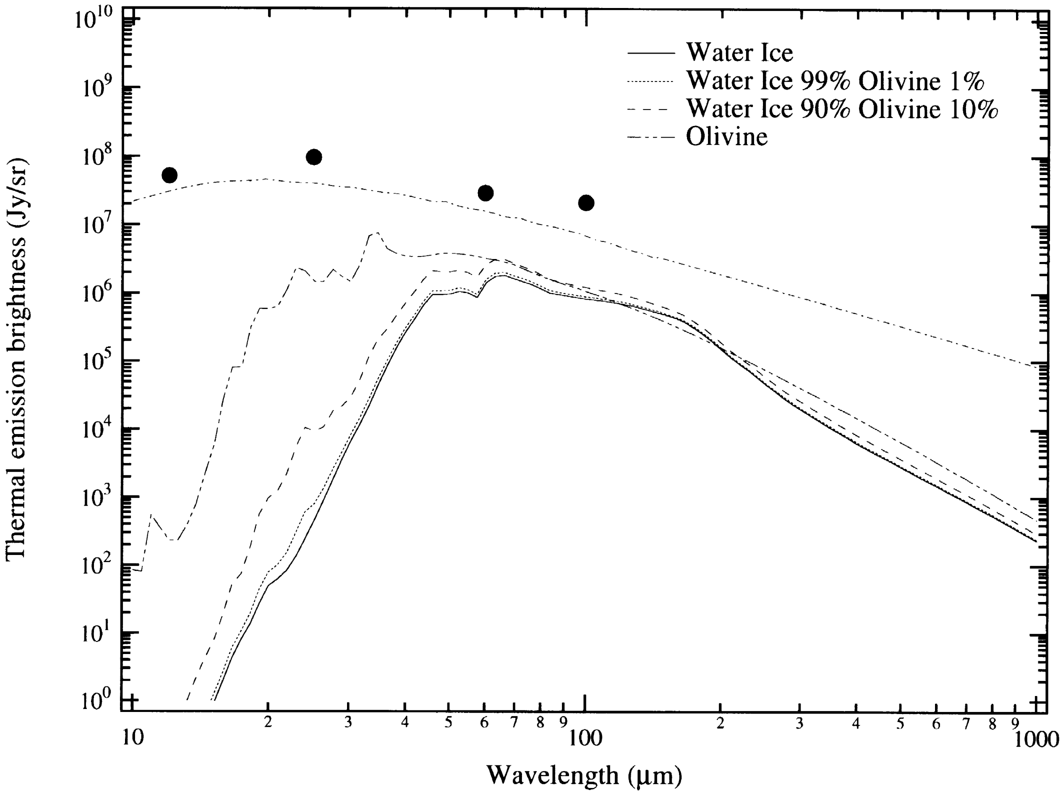


(b)

Fig. 2. Thermal emission from EKB dust cloud produced by mutual collisions of EKOs as a function of wavelength for (a) the maximum case of expected brightness and (b) the minimum case, where the both cases are detailed in the text. A volume fraction of olivine is 0%, 1%, and 10%. For comparison, IRAS data (Hauser *et al.*, 1984) (filled circles) and the model of zodiacal dust emission (Temi *et al.*, 1988) (dash-dotted line) are also plotted for the foreground zodiacal emission (see text).



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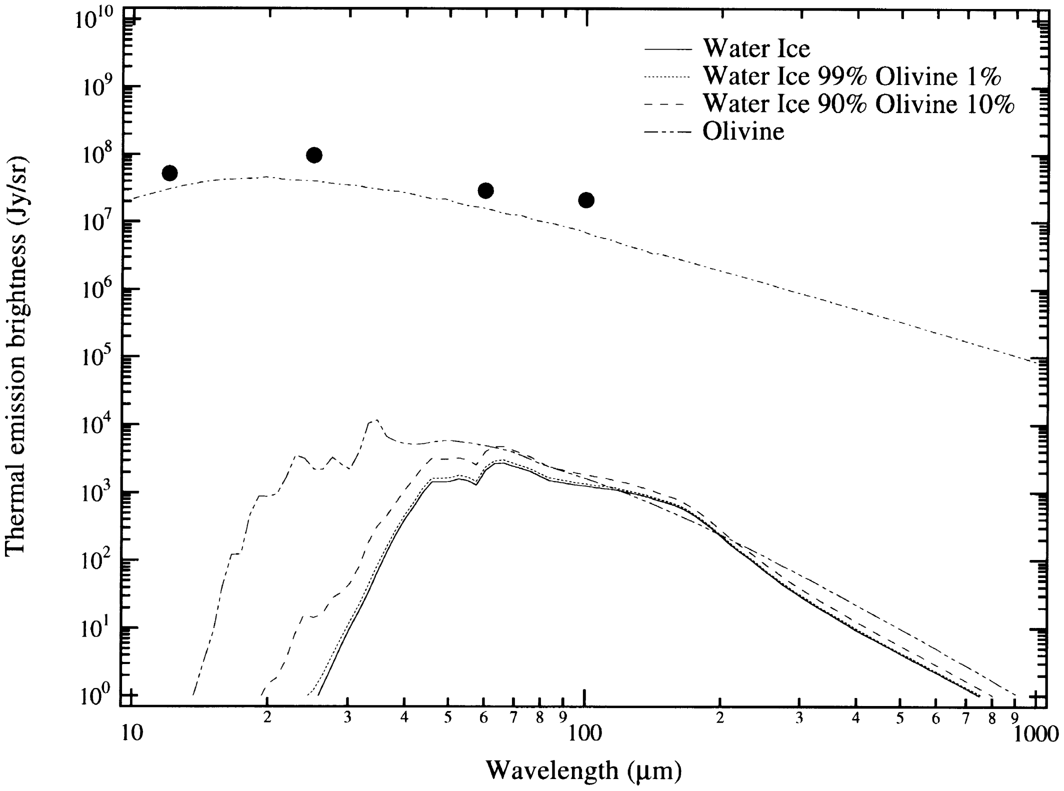

(b)

Fig. 3. The same as Fig. 2, but for the EKB dust cloud produced by interstellar dust impacts on EKOs.

estimated to be from 0.1 to about 70. Since the interstellar dust impacts on EKOs provide only small dust grain with radii less than about 10 μm (Yamamoto and Mukai, 1998), we set $a_1 = 10^{-5}$ cm and $a_2 = 10^{-3}$ cm. Consequently, the value of C_0 is calculated to be 3×10^{-25} to 2×10^{-22} from Eq. (5).

From $n(a, r)$ and C_0 estimated above, we estimate the total mass of dust in EKB. We assume that the EKB is a band with thickness of 16 deg around ecliptic, with solar distance between 30 AU and 50 AU (Jewitt and Luu, 1995), and the density of grain material is 1 g cm^{-3}. In this case, the total mass of dust existing in EKB produced by mutual collisions of EKOs is 2×10^{-8} M$_\oplus$ $\sim$ 3×10^{-6} M$_\oplus$, and those produced by the interstellar dust impacts is 2×10^{-9} M$_\oplus$ $\sim$ 2×10^{-6} M$_\oplus$ where M$_\oplus$ is the Earth mass. On the other hand, the total mass of EKOs with diameters larger than 6 km inside 50 AU is estimated to be from 0.1 M$_\oplus$ to 0.4 M$_\oplus$ (Stern, 1998).

Applying these values into Eq. (3), we calculated the thermal emission from EKB dust cloud at $e = 90^\circ$ as a function of wavelength for the case of mutual collisions of EKOs (Fig. 2) and for the case of interstellar dust impacts (Fig. 3). There is a spectral feature of water-ice at around 60 μm in Figs. 2 and 3. For comparison, the result for higher refractory material, that is the pure olivine, is also shown.

After leaving EKB, some EKB dust grains suffer from the mutual collisions of grains and interstellar dust impacts (Liou *et al.*, 1996). A disruption of grain provides an increase of total cross-sectional area with decreasing a solar distance of EKB dust grain under the Poynting-Robertson effect. In this scenario, the EKB dust cloud has total cross-sectional area smaller than that observed at 1 AU. This is the case of $f < 1$ (Fig. 2(b) and Fig. 3(b)). On the other hand, the loss of grains due to dynamical processes such as gravitational scattering, the solar radiation pressure, and due to sublimation could remove the dust grains from the Solar System, before the grains reach inner Solar System (Liou *et al.*, 1996). This is the case of $f > 1$ (Fig. 2(a) and Fig. 3(a)).

For comparison, IRAS data in ecliptic plane (Hauser *et al.*, 1984) for foreground zodiacal emission at $e = 91.1^\circ$ are plotted in Figs. 2 and 3 as filled circles. In addition, the model of zodiacal dust emission at $e = 90^\circ$ (Temi *et al.*, 1988) in $\lambda = 10$–200 μm is plotted (dash-dotted line). For the model of zodiacal dust emission beyond $\lambda = 200$ μm, we extrapolated the results of Temi *et al.* (1988), assuming the representative zodiacal emission temperature of 244 K (Hauser *et al.*, 1984) and blackbody of the grains. The thermal emission of EKOs is fainter than that of IRAS in all cases considered here. This means that it is difficult to find the thermal emission spectrum of EKB dust cloud in the previous infrared observations from the Earth. On the other hand, for the maximum case shown in Figs. 2(a) and 3(a), the thermal emission from EKB dust cloud should be comparable than the foreground zodiacal emission in far-infrared and submillimeter regions. In this case, a spatial variation of the color between mid-infrared and submillimeter regions might be observed.

It is likely that the EKB dust cloud has a band structure with a thickness of about 10 to 20 degrees around the ecliptic as that of parent EKOs (Jewitt and Luu, 1995). The maximum values of the thermal emission from EKB dust cloud attains about tens of percentages of that of foreground zodiacal emission. In this case, the detail scanning of thermal radiation along a line perpendicular to the ecliptic plane may reveal the contribution of EKB dust cloud to the foreground zodiacal dust cloud. Since the gradient of brightness depends on the latitudinal distribution of EKB dust cloud, it is important to know the spatial distribution of parent EKOs. Up to now, no available data for the spatial distribution of whole EKOs exist. Thus, more detailed analysis of dynamical properties of EKB dust grain is required to construct a reliable cloud model, and predict the detectability of EKB dust cloud from the Earth.

It is worthwhile to investigate various scenarios for heliocentric distribution of EKB dust cloud. We calculated the thermal emission from EKB dust cloud when $n(a, r) \propto r^{-1}$ and $n(a, r) \propto r^{-2}$, and found that there are no significant defference between these results and the results for the case of constant distribution of EKB dust model. Thus, we conclude that the heliocentric distribution of EKB dust cloud does not have a significant influence on the total thermal emission.

While the interstellar dust impacts on EKOs provide only small dust grains with radii less than 10 μm, the mutual collisions of EKOs provide both small and large dust grains. However, there are no significant difference of the thermal emission spectrum between the former and the latter in the wavelength shorter than about 60 μm. Since we used the model of number density of $n(a) \propto a^{-3.5}$, the small grains of EKB dust cloud have the large total cross-sectional area compared to large dust grains. Namely, the thermal emission mainly comes from the small dust grains, except for longer wavelength domain.

Furthermore, we investigated the sensitivity of our results to the value of the minimum radius of EKB dust grain a_1 in Eq. (3). By using $a_1 = 0.01$ μm, corresponding to the radius of small refractory particle found in cometary grain (e.g., McDonnell *et al.*, 1986), we reexamined the thermal radiation from EKB dust cloud. We found that the change of a_1 from 0.1 μm to 0.01 μm leads to a decrease of the total thermal radiation one third of that for $a_1 = 0.1$ μm.

4. Summary

We estimated the temperatures of EKB dust grains, based on the model of heterogeneous icy material consisting of small refractory inclusions embedded in icy matrix such as cometary dust. It is found that the dust grain in EKB has temperature, which depends on its radius, ranging from 20 K to 50 K. Applying the results of temperature for EKB dust grains, we examine the thermal emission from EKB dust cloud produced by the mutual collisions of EKOs and by the interstellar dust impacts on EKOs. The thermal emission of icy grain with small refractory inclusions shows the spectral feature of water-ice at the wavelength of about 60 μm. Since the predicted thermal emission from EKB dust cloud is fainter than that of IRAS data, however, it seems to be difficult to find a sign of thermal emission from EKB dust cloud in the past observations from the Earth.

The maximum case of thermal emission from EKB dust cloud presented here becomes to be comparable to that of foreground zodiacal emission at the wavelength of about tens of μm to hundreds of μm. When the EKB dust cloud has a narrow spatial band structure with a thickness of about 10 to 20 degree around the ecliptic as predicted for EKOs (Jewitt and Luu, 1995), the scanning of thermal radiation along a line perpendicular to the ecliptic plane may give a hint of the presence of EKB dust cloud in the future observations.

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S. Yamamoto (e-mail: yamachan@komadori.planet.kobe-u.ac.jp) and T. Mukai (e-mail: mukai@kobe-u.ac.jp)