OUTWARD MOTION OF POROUS DUST AGGREGATES BY STELLAR RADIATION PRESSURE IN PROTOPLANETARY DISKS

RYO TAZAKI¹ AND HIDEKO NOMURA²

¹ Department of Astronomy, Graduate School of Science, Kyoto University, Kitashirakawa-Oiwake-cho, Sakyo-ku, Kyoto 606-8502, Japan; razaki@kasastro.kyoto-u.ac.jp
² Department of Earth and Planetary Sciences, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan

Received 2014 October 24; accepted 2014 November 17; published 2015 January 21

ABSTRACT

We study the dust motion at the surface layer of protoplanetary disks. Dust grains in the surface layer migrate outward owing to angular momentum transport via gas-drag force induced by the stellar radiation pressure. In this study we calculate the mass flux of the outward motion of compact grains and porous dust aggregates by the radiation pressure. The radiation pressure force for porous dust aggregates is calculated using the T-Matrix Method for the Clusters of Spheres. First, we confirm that porous dust aggregates are forced by strong radiation pressure even if they grow to be larger aggregates, in contrast to homogeneous and spherical compact grains, for which radiation pressure efficiency becomes lower when their sizes increase. In addition, we find that the outward mass flux of porous dust aggregates with monomer size of 0.1 μm is larger than that of compact grains by an order of magnitude at the disk radius of 1 AU, when their sizes are several microns. This implies that large compact grains like calcium–aluminum-rich inclusions are hardly transported to the outer region by stellar radiation pressure, whereas porous dust aggregates like chondritic-porous interplanetary dust particles are efficiently transported to the comet formation region. Crystalline silicates are possibly transported in porous dust aggregates by stellar radiation pressure from the inner hot region to the outer cold cometary region in the protosolar nebula.

Key words: comets: general – protoplanetary disks – radiation: dynamics – solid state: refractory

1. INTRODUCTION

Protoplanetary disks (hereafter PPDs) are formed around the protostar and are thought to be the site of ongoing planet formation. The present-day solar system provides useful insights into the planet formation theory. Among them, there have been various debates about the origin of crystalline silicates in comets. Spectroscopic observations of comets have revealed that comets contain a substantial amount of crystalline silicates. The mass ratio of crystalline silicates to total (amorphous+crystal) silicates has a wide variety, for example, 70% for C/2001 Q4 (Wooden et al. 2004; Ootsubo et al. 2007), 30%–35% for 73P/S-W3 (Harker et al. 2011; Sitko et al. 2011), and 14% for C/2007 N3 (Woodward et al. 2011). Crystallinity is a smoking gun of thermal processing; however, comets are thought to be formed at the outer cold region of PPDs, where thermal processing is not likely to occur.

In general, crystalline silicate is formed by (1) annealing of amorphous silicate and (2) direct condensation from gas phase (e.g., Gail 2010). Annealing of amorphous silicate is a process of rearrangement of lattice structure using the external thermal energy. Laboratory experiments show that the crystallization timescale is $10^6$ yr for $T = 800$ K and 1 yr for $T = 1000$ K (e.g., Murata et al. 2009). In the case of vaporization and subsequent gas-phase condensation, the gas temperature is required to be at least $1380 \sim 1310$ K at $10^{-4}$ bar (Lodders 2003). This is a rather high temperature compared with that of comet formation regions, where it is tens of kelvins.

Since crystalline silicates are depleted in the interstellar medium, which is due to cosmic-ray hits or particle bombardment (Kemper et al. 2004, 2005), crystalline silicates must be formed in the PPDs. Indeed, many observations showed the presence of crystalline silicates in the PPDs around T Tauri stars (Bouwman et al. 2008; Olofsson et al. 2009; Watson et al. 2009), Herbig Ae/Be stars (Juhász et al. 2010), and young brown dwarf stars (Riaz et al. 2012). However, the formation location for the crystalline silicate is still being debated. One possibility is annealing or condensation at the inner region of PPDs, where the viscous heating yields a high-temperature environment (Gail 2004). Another possibility is an in situ annealing at a larger distance from the central star by a shock wave (Desch & Connolly 2002; Harker & Desch 2002) or annealing inside the clump fragmented from a massive disk (Vorobyov 2011). The other possibility is an episodic heating by intense radiation from a central star in outburst phase. Such an episodic heating event could anneal the amorphous silicate in the surface layer of PPDs (Abrahám et al. 2009; Juhász et al. 2012).

Chondritic porous interplanetary dust particles (CP-IDPs) can constrain the origin of crystalline silicates in comets, since they are considered to be of cometary origin (e.g., Messenger et al. 2013). CP-IDPs are highly porous aggregates of submicron dust grains mainly made of crystalline silicate (enstatite and forsterite) and amorphous silicate called GEMS (glass with embedded metal and sulfides). Crystalline morphology found in enstatite in CP-IDPs, such as enstatite whisker or platelet, suggests that the enstatite is formed via direct condensation from the gas phase (Bradley et al. 1983). The formation of enstatite via condensation at the inner region is also suggested by both theoretical calculations based on the equilibrium condensation model in PPDs (Gail 2004) and observations (Bouwman et al. 2008; Juhász et al. 2010). Moreover, although the origin of GEMS is still controversial, recent studies suggest that GEMS can be formed via nonequilibrium condensation from the gas phase (Keller & Messenger 2011; Matsuno et al. 2014). Therefore, it is possible to form most of the components in CP-IDPs at the inner region of PPDs.

While processed materials in CP-IDPs are formed at the inner region (less than 1 AU), comets are formed at the outer region
of PPDs (more than 30 AU, although it is still unclear). Thus, it is suggested that in the early phase of PPDs, there was a large-scale radial mixing that connects the inner and the outer regions of protoplanetary disks. In order to explain this large-scale radial mixing, many models have been proposed so far. One of the plausible ideas for radial mixing is a diffusion of dust regions of protoplanetary disks. In order to explain this large-scale radial mixing that connects the inner and the outer PPDs, and we discuss the result. Finally, in Section 4 we state the implications to the origin of cometary grains.

2. MODEL

In this paper we adopt cylindrical coordinates \((r, \phi, z)\) and assume an axisymmetric and geometrically thin disk.

### 2.1. Gas Disk

We assume that gas is in hydrostatic equilibrium in the vertical direction,

\[
-\frac{GM_s z}{(r^2 + z^2)^{3/2}} - \frac{1}{\rho_g} \frac{\partial q_g}{\partial z} = 0,
\]

where \(G\) is the gravitational constant, \(M_s\) is the mass of the central star, and \(\rho_g\) and \(q_g\) are the density and pressure of gas, respectively. We neglect here the self-gravity of the disk. Suppose the disk is isothermal in the \(z\)-direction, the gas density is given by

\[
\rho_g(r, z) = \rho_g(r, 0) \exp \left( -\frac{z^2}{2h_g^2} \right),
\]

Here \(h_g\) is the gas scale height, defined as

\[
h_g = c_s/\Omega_{\text{K, mid}},
\]

where \(c_s\) is the sound speed and \(\Omega_{\text{K, mid}} = (GM_s/r^3)^{1/2}\) is the angular frequency at the midplane of Keplerian disks. The force balance in the radial direction with respect to the gas particle is

\[
r\Omega_g^2 - \frac{GM_r}{(r^2 + z^2)^{3/2}} - \frac{1}{\rho_g} \frac{\partial q_g}{\partial r} = 0.
\]

If we define \(\eta\) as a ratio of gas pressure and stellar gravity, \(\eta = -(r\Omega_g^2 \rho_g)^{-1}\frac{\partial q_g}{\partial r}\), then

\[
\Omega_g = \Omega_{\text{K, mid}}(1 - \eta)^{1/2},
\]

where we neglect higher orders than \((z/r)^2\).

For simplicity, the radial profiles of the gas density and temperature are assumed to have power-law forms, such that

\[
\rho_g(r, 0) = \rho_{g,0} \left(\frac{r}{1\text{ AU}}\right)^p,
\]

\[
T(r) = T_0 \left(\frac{r}{1\text{ AU}}\right)^q,
\]

where \(T\) is the temperature. Then the gas scale height in Equation (3) becomes

\[
h_g = h_0 \left(\frac{r}{1\text{ AU}}\right)^{(q+3)/2}.
\]

The surface density of the gas disk is reduced to

\[
\Sigma_g(r) = \int_{-\infty}^{\infty} \rho_g(r, z) dz = \sqrt{2\pi} \rho_{g,0} h_0 \left(\frac{r}{1\text{ AU}}\right)^{p+(q+3)/2}.
\]

Also, \(\eta\) can be written in the following form (Takeuchi & Lin 2002):

\[
\eta = -\left(\frac{h_g}{r}\right)^2 \left( p + q + \frac{q+3}{2} \frac{z^2}{h_g^2} \right).
\]

In this paper we adopt \(p = -2.25\), \(q = -0.5\), \(\rho_{g,0} = 2.83 \times 10^{-10} \text{ g cm}^{-3}\), \(h_0 = 3.33 \times 10^{-2} \text{ AU}\), and \(T_0 = 278 \text{ K}\). Then the disk mass within 40 AU is 0.01 \(M_\odot\), and this is
comparable to a minimum-mass solar nebula (Hayashi et al. 1985). Also, in this case $\eta$ is positive near the midplane, while it becomes negative at the surface layer ($z \gtrsim 1.5 h_*$). Therefore, the gas disk rotates with sub-Keplerian velocity near the midplane and with super-Keplerian velocity at the surface layer.

The gas disk accretes onto the star owing to angular momentum transport induced by the MHD turbulence. The conservation of mass and angular momentum is reduced to

$$v_{g,r} = -\frac{3v}{r} \ln(\Sigma_g vz^{1/2}) - \frac{\ln r}{\partial \ln r}.$$  \hskip 0.5cm (11)

For the model of turbulent viscosity, we assume the $\alpha$-model (Shakura & Sunyaev 1973),

$$v = \alpha c_s h_g,$$  \hskip 0.5cm (12)

where $\alpha$ is a nondimensional quantity that indicates the strength of turbulent viscosity. We adopt $\alpha = 10^{-3}$ and assume that it is constant in the vertical direction in this paper.

### 2.2. Dust Disk

For dust grains smaller than the mean free path of gas molecules, Epstein’s law is applicable. The mean free path of gas molecules in the disks is given by

$$\lambda_{\text{mfp}} = \frac{\mu m_H}{\sigma_{\text{mol}} \rho_g} = 6.9 \left(\frac{r}{1 \text{ AU}}\right)^{2.25} \text{ cm},$$  \hskip 0.5cm (13)

where $\mu = 2.34$ is the mean molecular mass, $m_H$ is the mass of hydrogen atoms, and $\sigma_{\text{mol}} = 2 \times 10^{-15} \text{ cm}^2$ is the collision cross section of gas molecules. The grain radius we treat in this paper is always smaller than the mean free path. Epstein’s law of gas drag force is given by

$$F_{\text{drag}} = -\frac{4}{3} \rho_g \sigma v_t v,$$  \hskip 0.5cm (14)

where $v_t = \sqrt{8 kT/\pi c_s}$ is the thermal velocity of gas, $\sigma$ is the geometrical cross section of dust grains, and $v$ is the relative velocity between gas and dust. The timescale of the gas drag force can be estimated as

$$t_s = \frac{mv}{|F_{\text{drag}}|} = \frac{3 m}{4} \rho_g v_t.$$  \hskip 0.5cm (15)

where $m$ is the mass of a dust particle. It represents the typical timescale in which dust grains lose their momentum by the gas drag force. This timescale is called the “stopping time,” and it is convenient to use the stopping time normalized by the dynamical time, $T_s = t_s \Omega_K$. In the case of $T_s \ll 1$, dust grains stop so quickly relative to gas that the dust grains move just like gas (well coupled). If $T_s \gg 1$, the gas drag force is ineffective; therefore, the dust grains move independently of gas (decoupled).

If we assume that the distribution of dust particles in the vertical direction is controlled by turbulent mixing of gas, the density distribution of dust grains is derived as

$$\rho_d(r, z) = \rho_d(r, 0) \exp \left[-\frac{z^2}{2 h_g^2} - \frac{T_{\text{mid}}}{\alpha} \left(\exp \frac{z^2}{2 h_g^2} - 1\right)\right]$$  \hskip 0.5cm (16)

where $T_{\text{mid}}$ is the nondimensional stopping time at midplane (Takeuchi & Lin 2003). Note that the density distribution of dust grains deviates from the Gaussian distribution at high altitude ($z \gtrsim h_g$) since dust grains become decoupled from gas. $\alpha$ in Equation (16) is a nondimensional parameter for the turbulent diffusion coefficient, and we simply assume that $\alpha$ is the same as the parameter for the turbulent viscosity in Equation (12) in this paper.

The gas density at the midplane, $\rho_d(r, 0)$, is derived so that the dust surface density,

$$\Sigma_d(r) = \int_{-\infty}^{\infty} \rho_d(r, z) dz,$$  \hskip 0.5cm (17)

satisfies $\Sigma_d(r) = f_{\text{dust}} \Sigma_g(r)$, where $f_{\text{dust}}$ is the dust-to-gas mass ratio and we adopt $f_{\text{dust}} = 0.01$ in this paper.

The equation of motion of dust grains is

$$\frac{d v_{d,r}}{dt} = \frac{v_{d,r}^2 - (1 - \beta) \Omega_K^2 r}{t_s} - \frac{v_{g,r} - v_{g,t}}{t_s},$$  \hskip 0.5cm (18)

$$\frac{d}{dt}(v_{d,\phi} T_s) = -r \frac{v_{d,\phi} - v_g}{t_s},$$  \hskip 0.5cm (19)

where $v_{d,r}$ and $v_{d,\phi}$ are the radial and azimuthal velocities of dust grains, respectively, and $v_{g,r}$ is the azimuthal velocity of gas. $\beta$ is a ratio of radiation pressure and stellar gravity. We neglect the effect of Poynting–Robertson drag in both Equations (18) and (19) since it is negligible compared to the gas drag force in gas-rich protoplanetary disks (Takeuchi & Artymowicz 2001). Assuming $v_{d,\phi} - v_{g,\phi} \sim v_K$ and steady state, and solving Equations (5), (18), and (19), we get

$$v_{d,r} = \frac{v_{g,r} T_s^{-1} + (1 - \beta - \eta) v_K}{T_s + T_s^{-1}},$$  \hskip 0.5cm (20)

where $v_K = r \Omega_K$ is the Keplerian velocity. Equation (20) shows that the dust radial velocity is coincident with gas accretion velocity when the dust grains are well coupled to gas ($T_s \ll 1$), and the dust grains with large $\beta$ compared to $\eta$ can move outward when they are weakly decoupled from gas ($T_s \sim 1$). When the gas drag force is negligible, Equation (18) shows that the rotation frequency of dust particles becomes

$$\Omega_d = \Omega_K (1 - \beta)^{1/2},$$  \hskip 0.5cm (21)

and the dust particles orbit around the central star with sub-Keplerian frequency owing to radiation pressure in the surface layer.

In the optically thin surface layer where the stellar radiation is not absorbed by dust grains, the ratio is reduced to (Burns et al. 1979)

$$\beta_0 = \frac{F_{\text{RFP},0}}{F_{\text{grav}}} = K \left(\frac{4}{m}\right) \int_0^\infty Q_{\text{RFP}}(x, m) B_3(T_s) d\lambda,$$  \hskip 0.5cm (22)

where $K = \pi R_c^2 / (GM_* c)$ is a constant, $R_c$ is the radius of the central star, and $B_3(T_s)$ is the Planck function at the effective temperature of the central star, $T_s$, and the wavelength of incident radiation, $\lambda$. We assume $M_* = M_\odot$ and $T_s = 5778 K$, which is a plausible value for the stellar effective temperature in the outburst phase (e.g., Juhász et al. 2012). $Q_{\text{RFP}}(x, m)$ is the efficiency of radiation pressure, and $x$ and $m$ are the size parameter and the refractive index of dust grains, respectively.
(see Section 2.3 for more details). Both gravity and radiation pressure are inversely proportional to the square of the disk radius; hence, $\beta_0$ does not depend on the distance from the central star.

The presence of dust grains makes the protoplanetary disk optically thick. The irradiation from the central star and then the radiation pressure are reduced by dust absorption as $F_{RP} = F_{RP,0} \exp(-\tau)$, and $\beta$ becomes

$$\beta = \beta_0 \exp[-\tau(r, z)]. \quad (23)$$

We note that the contribution of stellar radiation scattered on dust grains is simply neglected in this study. We calculate the optical depth from the central star as

$$\tau(r, z) = \int_{r_m}^r \frac{\kappa_{\text{abs, disk}}}{\rho_d(r', z')} \sqrt{1 + \frac{z'^2}{r'^2}} \, dr',$$  \quad (24)

where $r_m$ is the inner radius of the disk, which is assumed to be $r_m = 0.1$ AU, and $\kappa_{\text{abs, disk}}$ is the mass absorption opacity; we simply adopt the typical value at visible wavelength, $\kappa_{\text{abs, disk}} = 100$ g cm$^{-2}$.

### 2.3. Dust Model

We deal with porous aggregates composed of a number of spherical monomers. BCCA (ballistic-cluster-cluster aggregation) and BPCA (ballistic-particle-cluster-aggregation) are widely used as models for porous aggregates. The degree of fluffiness can be described by the fractal dimension $D$, defined by

$$N \propto \left( \frac{s_c}{s_0} \right)^D, \quad (25)$$

where $N$ is the monomer number, $s_0$ is the monomer radius, and $s_c$ is the characteristic radius of porous aggregates. BCCA and BPCA show $D \sim 2.0$ and 3.0, respectively. The characteristic radius of porous aggregates is given by

$$s_c^2 = \frac{3}{5} s_g^2, \quad s_g = \left[ \frac{1}{2 N^2} \sum_i^N \sum_j^N (s_i - s_j)^2 \right]^{1/2},$$ \quad (26)

where $s_i, s_j$ are the position vectors of the $i$th and $j$th monomers (e.g., Mukai et al. 1992). In this paper, three types of dust grain, a monomer, compact grains, and porous aggregates are considered. We define the filling factor of porous aggregates as

$$f = N \left( \frac{s_0}{s_c} \right)^3. \quad (27)$$

Porous aggregates are assumed to be BCCA with 8, 16, 32, 64, 128, 256, 512, and 1024 monomers. The monomer radius of $s_0 = 0.1$ $\mu$m is adopted, which is a typical size of GEMS or crystalline enstatite. The dust physical density of olivine, $\rho_s = 3.3$ g cm$^{-3}$ (Draine & Lee 1984), is used.

#### 2.3.1. Optical Properties of Dust Grains

Optical properties, or the scattering and absorption by a particle, vary drastically depending on its size, shape, and chemical composition. The dependence on size and wavelength can be scaled by the size parameter,

$$x = ks = \frac{2\pi s}{\lambda}, \quad (28)$$

where $s$ is the size of the particle, $k$ is the wavenumber, and $\lambda$ is an incident wavelength. The other factor that controls optical properties is the refractive index of particles. It is convenient to use the complex representation of refractive index, $m = n + ik$, where $n$ and $k$ are the real part and imaginary part of the refractive index, respectively. Note that in this paper, the symbol $k$ denotes the wavenumber, while $k$ represents the imaginary part of the complex refractive index. The real part of $m$ determines the phase velocity in the medium, and the imaginary part represents the absorption by the medium. In this paper, the chemical composition of dust grains is assumed to be the astronomical silicate (e.g., Draine & Lee 1984; Weingartner & Draine 2001; Li & Draine 2001). It should be noted that astronomical silicates are amorphous, and in general optical constants differ between amorphous and crystal. An anisotropic crystal, such as an enstatite whisker, has different optical properties with respect to each crystalline axis; thus, the Mie Theory, and then the TMM, are not applicable without some approximation. Therefore, in this paper we simply assume homogeneous, isotropic amorphous silicate as a monomer.

Once we know the size parameter and complex refractive index, we can calculate absorption/scattering cross section. We define the efficiency for absorption and scattering as $Q_{\text{abs}} = C_{\text{abs}}/\sigma$ and $Q_{\text{sca}} = C_{\text{sca}}/\sigma$, where $C_{\text{abs/sca}}$ is the absorption/scattering cross section and $\sigma$ is the geometrical cross section of the dust particle. Using the absorption and scattering efficiency, we can describe the radiation pressure efficiency as

$$Q_{\text{RP}} = Q_{\text{abs}} + (1 - g)Q_{\text{sca}}, \quad (29)$$

where $g$ is the asymmetry parameter defined by $g = \langle \cos \theta \rangle$. Here $\theta$ is the scattering angle. The asymmetry parameter represents the degree of forward scattering. For the longer wavelength ($x \ll 1$), $g = 0$ owing to Rayleigh scattering and then $Q_{\text{RP}} \sim Q_{\text{ext}}$. Also in the Rayleigh regime, extinction efficiency is dominated by absorption efficiency. Eventually, $Q_{\text{RP}} \sim Q_{\text{abs}}$. If the size parameter is large ($x \gg 1$), the asymmetry parameter approaches unity and then $Q_{\text{RP}} \sim Q_{\text{abs}}$. The scattering plays an important role for radiation pressure when $x \approx 1$.

#### 2.3.2. Optical Properties of Porous Aggregates

We can calculate these optical properties using the Mie Theory if the grain is homogeneous, isotropic, and spherical (Bohren & Huffman 1983). However, in the case of inhomogeneous aggregates this semianalytical method is not applicable. In order to calculate the optical properties of porous aggregates, we need numerical methods.

One of the simplest ways is to use the Effective Medium Theory (EMT; e.g., Chýlek et al. 2000). This theory deals with porous aggregates as a sphere with effective optical constants. The EMT assumes that (1) incident light is static fields, which is approximately satisfied unless the inverse of the frequency of incident lights falls the timescale of polarization of monomer (Rayleigh limits) and (2) neglecting the interaction between monomer’s scattered fields. Therefore, in principle, the EMT cannot handle the shorter wavelength domain, where the higher order of Lorentz–Mie coefficients becomes important.

Another method commonly used is the discrete dipole approximation (DDA; Purcell & Pennypacker 1973; Draine & Flatau 1994). The advantage of DDA is applicability to arbitrarily shaped, inhomogeneous, and anisotropic particles. If the monomer is divided into $N_d$ dipoles, having the dipole polarizability determined via radiative reaction corrections.
The Astrophysical Journal, 799:119 (9pp), 2015 February 1

Tazaki & Nomura

(10-16)

(Draine 1988) and the lattice dispersion relation (Draine & Goodman 1993), the DDA can treat porous aggregates and yields correct results, when $N_D$ is taken to be large enough to converge the calculation. However, with increasing $N_D$, the computation of the DDA requires huge computing memory and long computing times. One way to reduce numerical costs is to replace spherical monomers as single dipoles (e.g., Okamoto & Xu 1998); however, this method is only applicable for $x_m < 1$.

The TMM for the Clusters of Spheres is also widely accepted method (e.g., Mishchenko et al. 1996; Okada 2008). This is one of the most rigorous methods of calculating optical properties of porous aggregates using the multisphere superposition method. The TMM is applicable to $x_c < 100$, where $x_c$ is a size parameter for the volume-equivalent sphere (e.g., Mishchenko et al. 2000).

The peak wavelength of the blackbody radiation at $T_\ast = 5778$ K is $\lambda_{\text{peak}} \sim 0.5 \mu m$, so that, at the peak wavelength, the size parameter for the monomer is $x_m \sim 1.25$ and the volume-equivalent size parameter is $x_c \sim 12.6$ when the monomer size is $0.1 \mu m$ and monomer number is $N = 1024$. Therefore, we can use the TMM. We use the code by Okada (2008), with which faster computation speed is available by adopting the quasi-orientation averaging. In our calculation, we averaged optical properties over 30 orientations for each aggregate.

3. RESULTS

First, we report the difference of the $\beta$-value, the ratio of the radiation pressure to stellar gravity, between porous aggregates and compact grains. Next, using the result, we calculate the radial velocity of dust grains at the surface layer and estimate the outward mass flux.

3.1. Radiation Pressure

We calculate $\beta$-values for porous aggregates and compact grains based on Equations (22) and (29) and plot them in Figure 1. For comparison, $\beta$ for porous aggregates with $s_0 = 0.01 \mu m$ is plotted in addition to our fiducial model with $s_0 = 0.1 \mu m$. In Table 1 we summarize the sizes of aggregates composed of $0.1 \mu m$ sized monomers and their $\beta$-values. The absorption and scattering cross sections are calculated using the Mie Theory for compact grains and using the TMM for porous aggregates. Properties of light scattering and absorption by porous aggregates will be discussed in R. Tazaki et al. (in preparation). Hence, we only describe $\beta$-value in this paper. In the case of compact grains, as the size increases, $\beta$-value also increases, when the grain size is small. When $x \sim 1$, the $\beta$-curve strongly depends on optical constants owing to resonance and the interference effect (see, e.g., Appendix B in Miyake & Nakagawa 1993). In the geometrical optics regime, where $x \gg 1$ and a monomer is optically thick, $Q_{\text{RP}}$ does not depend on the size parameter, and the $\beta$-value for the compact grains only depends on the area-to-mass ratio, that is, $\beta \propto s^{-1}$.

Therefore, as the size increases, the $\beta$-value for compact grains decreases. In contrast, in the case of porous aggregates the $\beta$-value remains high even if the monomer number or characteristic radius increases (e.g., Kimura et al. 2002; Kühler et al. 2007). As we mentioned in Section 2.3.1, if $x \ll 1$, absorption dominates the radiation pressure efficiency, $Q_{\text{RP}} \sim Q_{\text{abs}}$. In addition, in this regime the absorption cross section of BCCA can be simply described by superposition of the monomer’s absorption cross section, $C_{\text{abs}}(N) = NC_{\text{abs}}(N = 1)$ (e.g., Kolokolova et al. 2007; Kataoka et al. 2014). Therefore, $\beta_{\text{BCCA}}/\beta_{\text{N=1}} \propto N^0$.

In Figure 1, we also plot $\beta$-value obtained using effective medium theory with Maxwell–Garnett mixing rules (Chýlek et al. 2000) with filling factor defined by Equation (27) for comparison with TMM. In the case of $s_0 = 0.01 \mu m$, the result of effective medium theory does not deviate from that of TMM very much, although it does if $s_0 = 0.1 \mu m$. This is because, in the latter case, the size parameter of a monomer approaches

| $N$  | Characteristic Radius $x_c$ | $\beta$ |
|------|-----------------------------|--------|
| 1    | 0.1  | 0.73 |
| 8    | 0.33 | 0.69 |
| 16   | 0.46 | 0.68 |
| 32   | 0.74 | 0.67 |
| 64   | 1.04 | 0.66 |
| 128  | 1.41 | 0.65 |
| 256  | 2.34 | 0.64 |
| 512  | 3.09 | 0.64 |
| 1024 | 4.37 | 0.62 |

5 This is an open code, and one can download it from http://www.iup.uni-bremen.de/~alexk/page26.html.
unity, and then second- or higher-order Lorentz–Mie coefficients cannot be negligible and the EMT approximation breaks down.

3.2. Outward Drift of Grains in the Surface Layer

Figure 2 shows the radial velocity of dust grains obtained from Equation (20). Above the photosphere (\( \tau = 1 \)), dust grains are exposed to stellar radiation pressure, and they move along the spiral-out orbit. Outward drift velocity becomes maximum where the nondimensional stopping time equals unity. In this case, \( v_{d,r} \mid \tau = 1 = \beta v_K / 2 \) when \( \beta > \eta \). \( \eta \) for compact grains with \( s = 4.37 \, \mu m \) (equivalent to the characteristic radius of BCCA with 1024 monomers) is \( \beta = 0.043 \), whereas \( \beta = 0.62 \) for porous aggregates. Therefore, the outward drift velocity for porous aggregates is 62% of the Keplerian velocity and 4.3% for compact grains. However, the velocity with which most of the mass is transported is relatively slower than this velocity because, just above the photosphere, dust grains are weakly coupled to gas, that is, \( T_s < 1 \) (see Figure 2). Since the dust density rapidly decreases as the height increases, the outward mass flux is determined by the radial velocity and dust density at the illuminated surface, or just above \( \tau = 1 \). At the surface layer, the radial velocity can be described approximately as \( v_{d,r}(r, z_{\text{sur}}) = v_{g,r} + \beta v_K T_s \), where we neglect \( \eta \) since \( \eta \ll \beta \) and omit the second order of \( T_s \).

We define the blowout timescale as \( t_b = r / |v_{d,r,z_{\text{sur}}}| \) and plot it in Figure 3. \( z_{\text{sur}} \) is the height where \( \tau = 1 \). Figure 3 also shows that the monomer or porous aggregates blow outward with a shorter timescale than compact grains, since \( \beta \) of porous aggregates is larger than that of compact grains by an order of magnitude. It is also inferred that the porous aggregates cannot move beyond around 200 AU before dispersal of a disk if we consider that the disk dispersal timescale is on the order of megayears (e.g., Hernández et al. 2008). Note that since the stopping times of porous aggregates and compact grains are different, the height of the illuminated surface is also different between them. Thus, the difference in blowout timescales of compact grains and porous aggregates comes from both \( \beta \)-value and \( T_s \).

Figure 3 implies that the outward flow velocity at the surface layer is high. However, the outward mass flux is not very large since only a small fraction of dust grains can reside in the optically thin surface layer. We evaluate the mass flux by surface outward flow defined by

\[
F_{\text{out}}(r) = 2 \int_{z_{\text{sur}}}^{\infty} 2 \pi r \rho_d(r, z) |v_{d,r}(r, z)| dz, \tag{30}
\]

where the factor 2 arises from both sides of the disk. The outward mass flux can be written approximately as

\[
F_{\text{out}} \sim 2 \pi r \rho_d(r, z_{\text{sur}}) \Sigma_{d, \text{sur}}, \tag{31}
\]

where \( \Sigma_{d, \text{sur}} = 2 \int_{z_{\text{sur}}}^{\infty} \rho_d(r, z) dz. \)

In Figure 4 we plot the outward mass flux at \( r = 1 \) AU as a function of grain radius. Figure 4 is qualitatively similar to Figure 1. Outward mass flux is \( 1.4 \times 10^{12} \, g \, s^{-1} \) for porous aggregates with \( N = 1024 \), whereas it is \( 1.7 \times 10^{11} \, g \, s^{-1} \) for compact grains with the same radius. Thus, porous aggregates are blown out more effectively than compact grains by an order of magnitude. What we should mention here is that the porous aggregation itself does not affect the outward mass flux of dust grains. Even if they grow to be a larger size, porous aggregates can move outward as effectively as a monomer, whereas compact grains cannot since the radiation pressure becomes small. \( \beta \) of porous aggregates remains constant as they grow, until their fractal dimension deviates from 2, owing to
compaction such as by collisional compression (e.g., Okuzumi et al. 2012).

Juhász et al. (2012) reported that crystalline features are detected from the inner region of PPDs soon after the outburst; however, these crystalline features decrease as time goes on. They construct a model and conclude that depletion of the crystalline grains after the outburst cannot be explained by the vertical mixing, and they are transported to large disk radii owing to, for example, radiation pressure.

3.3. Timescales of Vertical Dust Dynamics

In the previous section, we did not take into account vertical motion of dust grains. In PPDs, dust grains can also move in the vertical direction owing to stellar gravity and turbulent mixing. Once grains sink into the optically thick region, they cannot be exposed to the radiation pressure any more. Hence, it is valuable to mention here timescales of vertical motion and radial motion.

For simplicity, only settling and turbulent stirring are considered as the vertical motion of dust grains. Dust grains settle down to the disk midplane owing to the stellar gravity and experience the gas drag force. Thus, the settling velocity $v_{\text{sett}}$ can be determined by the balance between the stellar gravity and the gas drag force, and the settling timescale can be described by

$$t_{\text{sett}} = \frac{z}{v_{\text{sett}}} = \frac{4 \sigma}{3 m} \frac{\rho_g v_t}{\Omega_{K,\text{mid}}}$$

(Dullemond & Dominik 2004). Since the gas density decreases as disk height increases, the settling timescale becomes small at the large height of the disk.

Meanwhile, dust grains are stirred up by turbulent gas. The timescale of turbulent diffusion can be written in the form of $t_{\text{diff}} = z^2 / D_{\text{diff}}$, where $D_{\text{diff}}$ is the diffusion coefficient of dust grains and depends on (1) the strength of turbulence and (2) the degree of coupling between gas and dust. Since the strong turbulence yields the large diffusion coefficient, the diffusion coefficient is set to be proportional to the turbulent viscosity of gas, $\nu$. On the other hand, if dust grains are completely decoupled from gas, then the diffusion coefficient must be zero. Thus, we get $D_{\text{diff}} = \nu / Sc$, where $Sc$ is the Schmidt number, defined by $Sc = 1 + St$ (Cuzzi et al. 1993), and $St$ is the Stokes number, defined by $St \equiv (v_t / c_s) T_s$. For the well-coupled case, the Schmidt number approaches unity, and for the completely decoupled case, this number goes to infinity. If we adopt the $\alpha$ model for the turbulent viscosity (Equation (12)), we get the stirring timescale,

$$t_{\text{stir}} = \frac{Sc}{\alpha \Omega_{K,\text{mid}}} \frac{z^2}{h_g^2}.$$  

We compare the blowout timescale and the timescale of vertical dynamics (settling and stirring). Figure 5 shows vertical timescales of porous aggregates and compact grains. The depletion latitude of dust grains can be determined by the balance between $t_{\text{diff}}$ and $100 t_{\text{sett}}$ (Dullemond & Dominik 2004), and $100 t_{\text{sett}}$ is also plotted with the dashed line in Figure 5. In the case of porous aggregates, the blowout timescale is shorter than vertical dynamical timescales. Therefore, porous aggregates can
be blown out ballistically. In contrast, compact grains experience faster settling owing to their loose coupling to gas. Thus, they might be transported without sink to the disk midplane. To verify this effect, further calculation is necessary.

Outward mass flux for porous aggregates with \( n_0 = 0.1 \, \mu m \) and \( N = 1024 \) at 1 AU is \( 1.4 \times 10^{12} \, g \, s^{-1} \). Porous aggregates are expected to avoid fast settling, and then, optimistically, the total mass transported from the inner region to the comet formation region is at most \( 1.4 \times 10^{12} \, g \, s^{-1} \times Myr \sim 4.5 \times 10^{23} \, g \), which is comparable to the mass of the Kuiper Belt objects (e.g., Chiang et al. 2007).

4. IMPLICATIONS TO THE ORIGIN OF COMETARY GRAINS

Our results suggest that porous aggregates like CP-IDPs are blown out efficiently, whereas compact grains like calcium–aluminum rich inclusions (CAIs) are hardly blown out by radiation pressure in the surface layer of the protosolar nebula. It is worth noting that this result does not always contradict the results of the Stardust mission, which is a sample return mission from comet 81P/Wild 2 conducted by NASA. Stardust samples showed that comet 81P/Wild 2 contains not only crystalline silicate but also refractory grains such as CAIs and chondrule fragments that are usually found in meteorites (Brownlee 2014, and references therein). However, crystallographically, crystalline silicates found in collected Stardust samples and CP-IDPs have different properties. For instance, the enstatite whiskers in CP-IDPs tend to elongate in the [100]-direction, whereas enstatite in Stardust samples shows structure in the [001]-direction that is, when not equiaxial, commonly found in meteorites (Ishii et al. 2008). Since materials in comet 81P/Wild 2 resemble those in meteorites originating from asteroids, these results imply that in the early solar nebula comet 81P/Wild 2 could originally be a member of asteroids. Indeed, recent N-body calculations suggest that planetesimals could be scattered from a few AU to far beyond the current Neptunian orbit (e.g., Nagasawa et al. 2014). Therefore, if this were true, the origins of crystalline silicate in comet 81P/Wild 2 and CP-IDPs would not necessarily be the same, so that the large compact grains, like CAIs, are not necessary to transport from the inner disk to the outer disk by stellar radiation pressure.

5. SUMMARY

We have studied the surface outflow of dust grains by the stellar radiation pressure to explain the presence of crystalline silicate in comets. Especially, we took into account the porosity of dust grains to mimic the CP-IDPs that originate from comets. First, we confirmed that the radiation pressure for the porous aggregates is determined by the monomer's properties. Based on these results, we have calculated the outward mass flux at the surface layer. As a result, porous aggregates show much higher mass flux compared to the compact grains when their radii are equivalent. This suggests that porous aggregates like CP-IDPs are transported to the outer region of PPDs efficiently; thus, our model could be a possible candidate for the transport mechanism of crystalline silicates in porous aggregates from inner hot regions to outer cometary regions.

R.T. thanks Yasuhiro Okada for technical advice about the T-Matrix Method. R.T. also acknowledges useful discussions with Hiroshi Kimura and Junya Matsuno. The numerical calculations were carried out on SR16000 at YITP at Kyoto University. This work is supported by Grants-in-Aid for Scientific Research, 21303005 and 25400229.

REFERENCES

Abraham, P., Juhasz, A., Dullemond, C. P., et al. 2009, Natur, 459, 224
Balbus, S. A., & Hawley, J. F. 1991, ApJ, 376, 214
Bockelée-Morvan, D., Gautier, D., Hersant, F., Huré, J.-M., & Robert, F. 2002, A&A, 384, 1107
Bohren, C. F., & Huffman, D. R. 1983, Absorption and Scattering of Light by Small Particles (New York: Wiley)
Bouwman, J., Henning, T., Hillenbrand, L. A., et al. 2008, ApJ, 683, 479
Bradley, J. P., Brownlee, D. E., & Veblen, D. R. 1983, Natur, 301, 473
Brownlee, D. 2014, AREPS, 42, 179
Burns, J. A., Lamy, P. L., & Soter, S. 1979, Icar, 40, 1
Chiang, E., Lithwick, Y., Murray-Clay, R., et al. 2007, in Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil (Tucson, AZ: Univ. Arizona Press), 895
Chylek, P., Videen, G., Geldart, D. W. J., Bobbie, J. S., & Tso, H. C. W. 2000, Effective Medium Approximations for Heterogeneous Particles, ed. M. I. Mishchenko, J. W. Hovenier, & L. D. Travis (San Diego, CA: Academic Press)
Ciesla, F. J. 2007, Sci, 318, 613
Ciesla, F. J. 2009, Icar, 201, 655
Cuzzi, J. N., Davis, S. S., & Dobrovolskis, A. R. 2003, Icar, 166, 385
Cuzzi, J. N., Dobrovolskis, A. R., & Champaign, J. M. 1993, Icar, 106, 102
Desch, S. J., & Connolly, H. C., Jr. 2002, M&PS, 37, 183
Draine, B. T. 1988, ApJ, 333, 848
Draine, B. T., & Flatau, P. J. 1999, JOSAA, 11, 1491
Draine, B. T., & Goodman, J. 1993, ApJ, 405, 665
Draine, B. T., & Lee, H. M. 1984, ApJ, 285, 89
Dullemond, C. P., & Dominik, C. 2004, A&A, 421, 1075
Fromang, S., Lyra, W., & Masset, F. 2011, A&A, 534, A107
Gail, H.-P. 2001, A&A, 378, 192
Gail, H.-P. 2004, A&A, 413, 571
Gail, H.-P. 2010, in Avestroineralogy, ed. T. Henning ( Lecture Notes in Physics, Vol. 815 (Berlin: Springer), 61
Harker, D. E., & Desch, S. J. 2002, ApJL, 565, L109
Harker, D. E., Woodward, C. E., Kelley, M. S., et al. 2011, ApJ, 141, 26
Hayashi, C., Nakazawa, K., & Nakagawa, Y. 1985, in Protostars and Planets II, ed. D. C. Black & M. S. Matthews (Tucson, AZ: Univ. Arizona Press), 1100
Hernández, J., Hartmann, L., Calvet, N., et al. 2008, ApJ, 686, 1195
Hughes, A. L. H., & Armitage, P. J. 2010, ApJ, 719, 1633
Ishii, H. A., Bradley, J. P., Ovi, D. R., et al. 2008, Sci, 319, 447
Juhasz, A., Bouwman, J., Henning, T., et al. 2010, ApJ, 721, 431
Juhasz, A., Dullemond, C. P., van Boekel, R., et al. 2012, ApJ, 744, 118
Katoaka, N., Okuzumi, S., Tanaka, H., & Nomura, H. 2014, A&A, 568, A42
Keller, C., & Gail, H.-P. 2004, A&A, 415, 1177
Keller, L. P., & Messenger, S. 2011, GeCoA, 75, 5336
Kemper, F., Vriend, W. J., & Tielens, A. G. G. M. 2004, ApJ, 609, 826
Kemper, F., Vriend, W. J., & Tielens, A. G. G. M. 2005, ApJ, 633, 534
Kimura, H., Okamoto, H., & Mukai, T. 2002, Icar, 157, 349
Köhler, M., Minato, T., Kimura, H., & Mann, I. 2007, AdSpR, 40, 266
Kolokolova, L., Kimura, H., Kiselev, N., & Rosenbush, V. 2007, A&A, 463, 1189
Li, A., & Draine, B. T. 2001, ApJ, 554, 778
Lodders, K. 2003, ApJ, 591, 1220
Matsuno, J., Tsuji, A., Aoki, J., et al. 2014, in Lunar and Planetary Inst. Technical Report, Vol. 45, Lunar and Planetary Science Conference (Houston, TX: LPI), 1335
Mishchenko, J. W. Hovenier, & L. D. Travis (San Diego, CA: Academic Press)
Mishchenko, M. I., Hovenier, J. W., & Travis, L. D. 2000, Light Scattering by Nonspherical Particles: Theory, Measurements, and Applications (San Diego, CA: Academic Press)
Miyake, K., & Nakagawa, Y. 1993, Icar, 106, 20
Mukai, T., Ishimoto, H., Kozasa, T., Blum, J., & Greenberg, J. M. 1992, A&A, 262, 315
Murata, K., Chihara, H., Koike, C., et al. 2009, ApJ, 697, 836
Nagasawa, M., Tanaka, K. K., Tanaka, H., et al. 2014, ApJL, 794, L7
Okada, Y. 2008, JQSRT, 109, 1719
Okamoto, H., & Xu, Y.-l. 1998, EP&S, 50, 577
Okuzumi, S., Tanaka, H., Kobayashi, H., & Wada, K. 2012, ApJ, 752, 106
Olofsson, J., Augereau, J.-C., van Dishoeck, E. F., et al. 2009, A&A, 507, 327
Ootsubo, T., Watanabe, J.-i., Kawakita, H., Honda, M., & Furusho, R. 2007, P&SS, 55, 1044
Purcell, E. M., & Pennypacker, C. R. 1973, ApJ, 186, 705
Riaz, B., Honda, M., Campins, H., et al. 2012, MNRAS, 420, 2603
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Sitko, M. L., Lisse, C. M., Kelley, M. S., et al. 2011, AJ, 142, 80
Takeuchi, T., & Artymowicz, P. 2001, ApJ, 557, 990
Takeuchi, T., & Lin, D. N. C. 2002, ApJ, 581, 1344
Takeuchi, T., & Lin, D. N. C. 2003, ApJ, 593, 524
Urpin, V. A. 1984, SvA, 28, 50
Vinković, D. 2009, Natur, 459, 227
Vorobyov, E. I. 2011, ApJL, 728, L45
Watson, D. M., Leisenring, J. M., Furlan, E., et al. 2009, ApJS, 180, 84
Weingartner, J. C., & Draine, B. T. 2001, ApJ, 548, 296
Wooden, D. H., Woodward, C. E., & Harker, D. E. 2004, ApJL, 612, L77
Woodward, C. E., Jones, T. J., Brown, B., et al. 2011, AJ, 141, 181