PHOTOPHORETIC FORCE ON FRACTAL AGGREGATES IN A PROTOPLANETARY DISK. J. B. Kimery[1], L. S. Matthews[2], and T. W. Hyde[2], [1]Rice University, Houston, Texas, 77005, USA [2]CASPER, Baylor University, Waco, Texas 76798, USA.

Introduction: Observations of inner planets in our own and other solar systems indicate that these planets are denser and more metal-rich than outer planets in the same systems [1]. This suggests that a force may sort coagulating dust particles in a protoplanetary disk (PPD) by composition, driving silicates away from a young star while leaving metals unaffected. The photophoretic force is an ideal candidate for this sorting mechanism [1], [2].

The photophoretic force occurs in a low-density gaseous environment. Gas particles colliding with a dust grain that has a temperature gradient across its surface are adsorbed and equilibrate with the surface temperature before being ejected. The net momentum transferred to the dust grain usually accelerates it away from its illuminated side and thus away from the light source [3].

As silicates have a lower thermal conductivity and thus develop a greater temperature gradient than metals, they experience a stronger photophoretic force. This mechanism could sort dust in a PPD such that metallic grains remain near a star, while silicates move outward [1]. As the dust coagulates to aggregates and then planetesimals, eventually forming planets, this sorting effect could produce metal-rich inner planets and rockier outer planets.

The photophoretic force has been has been theoretically and experimentally investigated for single spherical particles and mm-sized irregular chondrules [4]–[7]. This study focuses on irregular μm-sized aggregates built from spherical monomers, comparable in size to the dust aggregates found in PPDs.

Numerical Model: The drift velocity of aggregates subject to the photophoretic force is determined by calculating the momentum transferred as gas molecules collide with and are re-emitted from the surface. The surface of the aggregate is divided into many points. These points are used to determine the photon flux to each point, the temperature gradient across the grain, the flux of gas molecules incident on the surface, and finally the net momentum transfer to the aggregate. The simulation assumes a light source along a given direction. Each point is checked to determine whether the illumination direction is blocked by another monomer in the aggregate.

The average temperature of an aggregate was set equal to the mean gas temperature T, with the average temperature of a given monomer $\bar{T}_i$ determined by the fraction of its surface which is illuminated, such that shadowed monomers have a lower mean temperature than fully-illuminated monomers. The temperature of each point was then adjusted based on the illumination flux and the distance from the last illuminated point, as illustrated in Figure 1.

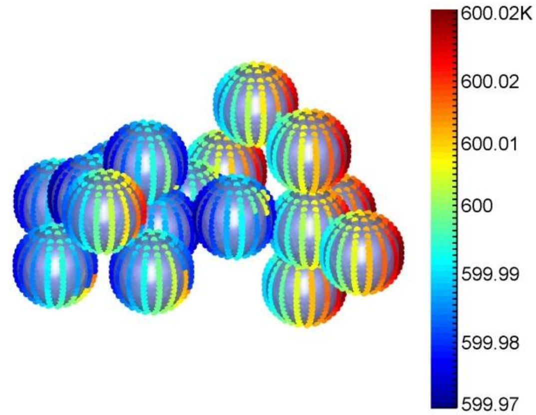

Fig. 1: Temperature gradient for an aggregate consisting of 17 monodisperse spheres, with the direction of illumination from the right. The hottest monomers have the largest illumination flux.

Momentum Transfer Calculations: The incoming gas particles are assumed to move on straight–line paths which are not blocked by other monomers within the aggregate, or open lines of sight (LOS). The number of particles impacting a surface per unit area per unit time is given by the flux, I

$$I = n \iiint v \cos \alpha f(v) d^3\bar{v} \quad (1)$$

where n is the particles' number density, $v \cos \alpha$ is the component of the velocity normal to the surface, and $f(v)$ is the Maxwellian velocity distribution.

The integral over the angles in (1) may be separated into an integral over the magnitude of the velocity and an integral over the angles

$$I = n \int_0^\infty v^3 f(v) dv \iint \cos \alpha \, d\Omega. \quad (2)$$

The integral $\iint \cos \alpha \, d\Omega$, the LOS_factor, depends on the open lines of sight at the surface. Points on an aggregate may have lines of sight which are blocked by other monomers within the aggregate, so the LOS_factor is calculated numerically for each patch. Details of the method are given in [8].

It is assumed that all gas particles which collide with the aggregate equilibrate with the local surface temperature before being ejected, as in [1]. Ejected particles may escape into space along an open LOS or collide with another monomer. If the rebound direction is blocked by another monomer in the aggregate, the gas is assumed to equilibrate with the new surface temperature, and the process repeats until an open rebound direction is selected. Rebounds continue until 99.99% of the gas has escaped; the remaining particles are assumed to rebound along the "average" open LOS for each patch.

The momentum transfer from an ejected gas particle is canceled if the gas particle collides with another monomer in the aggregate. Thus, the calculations consider only momentum transfer from the initial incoming gas particles and from gas particles rebounding along open paths. The magnitude of the change in momentum, and thus the force, at each point is given by

$$F = \left(\frac{p_{out}}{\Delta t}\right)_p - \left(\frac{p_{in}}{\Delta t}\right)_p = mA_p\left(I'_p\overrightarrow{v_s} - I_p\overrightarrow{v_g}\right) \quad (3)$$

where m is the mass of the gas particle, A_p the area of the patch surrounding a point, I_p the gas flux at point p calculated by Eq. 2, I'_p the flux adjusted for rebounding gas particles, v_s the velocity determined by the surface temperature and v_g the rms velocity of the gas. The direction of $\overrightarrow{v_s}$ is determined by the rebound direction, while the direction of $\overrightarrow{v_g}$ is along the average open LOS at that point. The average photophoretic force is determined by repeating the calculations numerous times and subtracting the force imparted by the gas when there is no temperature gradient present.

The drift velocity of the aggregate is calculated by

$$v_{\text{drift}} = F/m_d \cdot \tau \quad (4)$$

with τ, the gas grain coupling time, given by [9]

$$\tau = \gamma \frac{m_d}{\sigma} \frac{1}{\rho_g v_g} \quad (5)$$

with m_d the mass of the dust aggregate, σ its average cross-sectional area calculated as in [8], ρ_g the gas density, and γ experimentally determined to be 0.68 [9].

Results: Preliminary data are shown for two populations of aggregates, one built from monomers with a monodisperse size distribution (r = 1.7 μm) and the other built from monomers with a polydisperse size distribution (0.5 μm ≤ r ≤ 10 μm; $\langle r \rangle$ = 1.7 μm). The material is assumed to be silicate with a material temperature gradient of 10^4 K/m, and the surrounding gas temperature is set to be T = 600 K, as in [1]. The average force and drift velocity in the direction of illumination are compared to the results for spheres of equal mass, Figs. 2 and 3, respectively. Though smaller than those for spheres, the aggregate drift velocities produced by the photophoretic force (5-50 mm/s) are great enough to establish the photophoretic force as a potentially influential factor in PPD development.

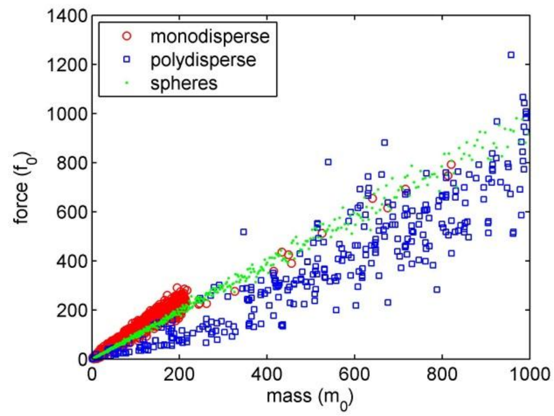

Fig. 2: Photophoretic force vs. mass, normalized to the force and mass of a sphere with r = 1.7 μm, F_0 = 2.83 × 10^{-28} N and m_0 = 5.14 × 10^{-14} kg.

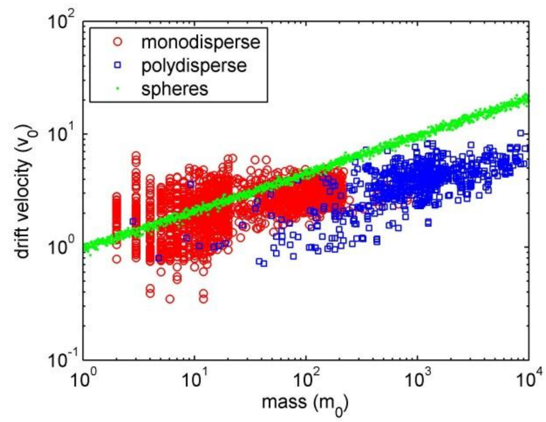

Fig. 3: Drift velocity vs. mass, normalized to the velocity and mass of a 1.7 μm-radius sphere, $v_{\text{drift},0}$ = 4.7 mm/s, m_0 = 5.14 × 10^{-14} kg. Both aggregate populations experience a smaller drift velocity than spheres of equivalent mass due to their larger cross-sectional areas.

References:

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