EFFECTS OF HEAT TRANSFER IN DUST AGGREGATES ON THE PHOTOPHORETIC FORCE.

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Introduction: The behavior of dust aggregates under the influence of the photophoretic force may play a role in the formation of planetary embryos in protoplanetary disks. Pebble accretion theories have arisen in response to the bouncing and fragmentation barriers for collisional aggregate growth [1-3]. Photophoresis has been proposed as a mechanism for aiding in the creation of high density dust regions, which are required by many pebble accretion theories [4]. Also, high planetary embryo surface luminosities caused by rapid embryo formation can generate temperature gradients in the surrounding gas which subjects dust to the photophoretic force [1], [5].

Photophoresis occurs when a dust grain that is suspended in a low density gaseous environment develops a temperature gradient across its surface due to an anisotropic radiation field. Gas molecules that come into contact with the dust grain equilibrate with the local surface temperature before being ejected again. The net momentum transferred to the grain generally causes the grain to accelerate away from the illumination source [6]. However, experiments have found that the photophoretic force can accelerate grains in any direction relative to the illumination direction, particularly in the case of aggregate grains [7], [8]. The magnitude and direction of the photophoretic force are dependent upon the magnitude and direction of the temperature gradient across the dust grain [7].

A numerical model was developed to investigate the photophoretic force acting on irregular μm-sized aggregates built from spherical monomers [10].While the model reproduced the general trends for the distributions of the magnitude and velocity of the photophoretic drift observed in the paired experimental study [7], a heuristic algorithm was used to calculate the temperature gradient for the dust aggregates. Furthermore, the model for the temperature gradient model did not predict negative photophoresis, as observed in experiment [7], [10].

This study builds on the numerical model for photophoresis developed in [10] by evaluating the effects of heat transfer processes in irregular aggregate grains.

Numerical Model: Aggregates are built from collections of spherical monomers. Each monomer is divided into discrete volumes defined by twenty patches spaced evenly over the surface, and an additional equivalent volume at the grain's center. The temperature of each volume is characterized by the temperature at the center of the volume, which is determined by summing all of the heat transfer processes to that volume: heat transfer to the surface by illumination, black body radiation, and collisions with gas molecules, and conduction between adjacent volumes.

Given an illumination source acting along a single direction, the magnitude of the radiation energy absorbed by a patch on a monomer's surface during a time Δt is given by

$$Q = (\vec{I}_i \cdot \hat{n}_i) \Delta\Omega \; LOS \; \Delta t \qquad (1)$$

where $\vec{I}_i$ is the illumination intensity with its direction given by the illumination direction, $\hat{n}$ is the unit vector normal to the surface patch, $\Delta\Omega$ is the solid angle subtended by the patch on the surface of the monomer, and LOS is a Boolean value, set to zero if the line of sight (LOS) along the illumination direction is blocked and one if the LOS is open.

The conduction of heat within a monomer during a time Δt is calculated from the sum of the conduction between all adjacent volumes, given by

$$Q = \frac{kA\Delta T}{l} \Delta t \qquad (2)$$

where A is the area of the contact surface between the volumes, ΔT is the temperature difference between the two volumes, and l is the distance between their respective center of mass.

Conduction between monomers occurs through circular contact areas, which can vary in size. This conduction is modeled as occurring between the two closest volumes on touching monomers and follows equation (2) except A is the contact area between monomers and l is half the distance between the centers of the touching monomers.

Aggregates are treated as black bodies where each patch can radiate to free space as well as to other monomers within the aggregate. One thousand straight line paths, or lines of sight (LOS), are drawn from each patch and then checked to determine if each LOS is blocked or open. Open LOS radiate to free space and the heat transfer is calculated by

$$Q = \sigma \, \Delta\Omega \left(T_p^4 - T_s^4\right) N \, \Omega_{LOS} \, \Delta t \qquad (3)$$

where σ is the Stefan-Boltzmann constant, T_p is the temperature of the volume, T_s is the temperature of space, Ω_{LOS} is the solid angle of a single LOS, and N is the number of free LOS. Blocked LOS radiate to other patches, where the heat transfer between two patches is calculated by

$$Q = \sigma \, \Delta\Omega \left(T_p^4 - T_b^4\right) n\Omega_{LOS} \, \Delta t \qquad (4)$$

where T_b is the temperature of the blocking patch, and n is the number of LOS from the first patch blocked by the second patch.

When a gas molecule comes into contact with the aggregate, it equilibrates with the local surface temperature before being ejected. The magnitude of this heat exchange is given by

$$Q = I_{gas}\, N\Omega_{LOS}\, \frac{3}{2} k\Delta T\, \Delta t \quad (5)$$

where I_{gas} is the gas flux and ΔT is the change in temperature of the gas molecule from the ambient gas temperature to the local aggregate surface temperature.

Results: Preliminary data are shown for a population of silicate aggregates generated using a combination of particle-cluster and cluster-cluster aggregation as in [11]. Each aggregate was simulated twice with different values for the contact area between monomers, once with contact areas calculated theoretically as in [12] yielding an area of 0.015 μm^2 and then with contact areas based on experimental images from [7] yielding an area of 1.815 μm^2. The gas temperature was assumed to be 300 K, the illumination intensity was 10 kW/m^2, and the average gas particle mas was $2.3m_p$, with m_p the proton mass

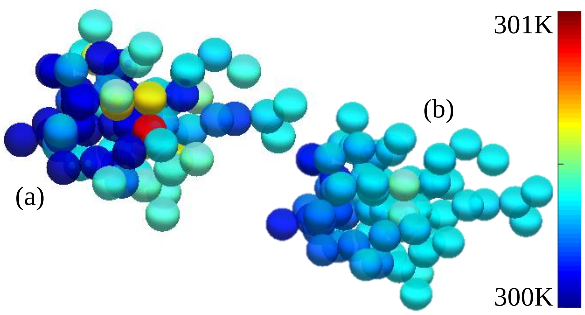

Fig. 1: Temperature gradient on a dust aggregate composed of 71 monomers calculated with small contact areas (a) and with large contact areas (b).

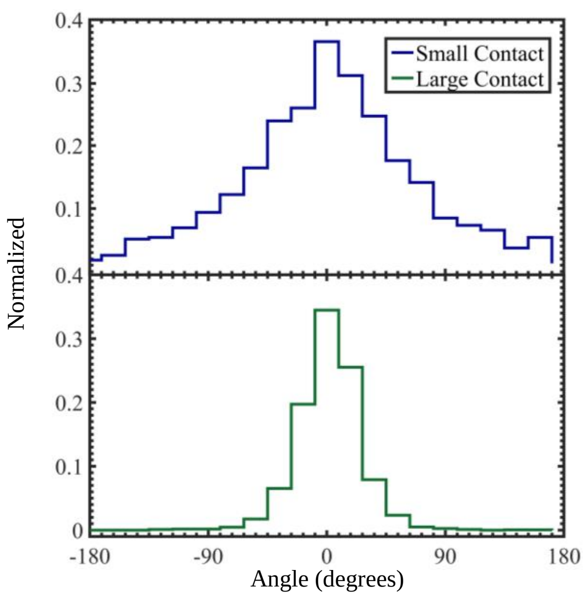

Fig. 2: Distribution of drift velocity with respect to the illumination direction for dust aggregates calculated with small (a) and large (b) monomer contact areas.

Large contact areas yielded linear temperature gradients, while small contact areas caused non-linear temperature gradients with hot spots often located in the center of the aggregate (Figure 1). As a result, aggregates with small contact areas have a larger variance in drift velocity direction than aggregates with large contact areas (Figure 2). Both populations produced negative photophoresis and the distribution of the drift velocity direction is representative of the observations in [7].

Preliminary results show that the small contact areas produce a larger variance in the magnitude of the photophoretic force and drift velocity than the large contact areas. However, the average drift velocity is the same for both contact areas and is weakly correlated with the number of monomers in an aggregate (Figure 3). Future work is will examine larger aggregates.

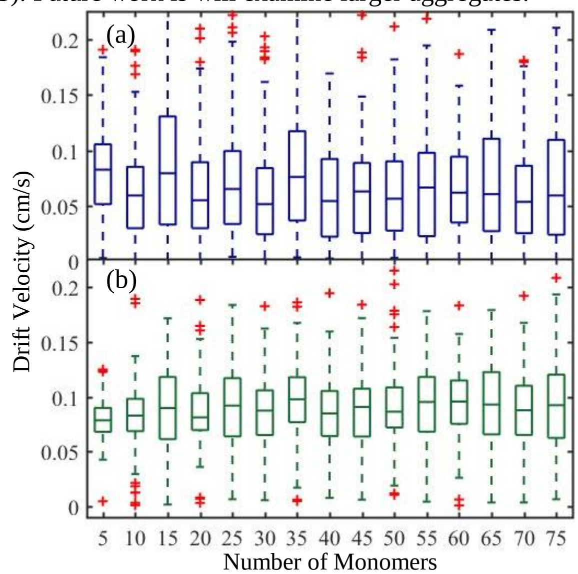

Fig. 3: Drift velocity vs. number of monomer calculated with small contact areas (a) and with large contact areas (b).

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