Photophoretic Force on Fractal Aggregates in a Protoplanetary Disk

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Abstract—The photophoretic force may impact planetary formation by sorting the dust in protoplanetary disks (PPDs) by composition. This numerical simulation studied the photophoretic force on fractal dust aggregates of \( \mu \text{m}-\text{scale} \) radii. In general, the force on the aggregates (and the corresponding drift velocity) was less than the force on comparable spheres, an unexpected result that may be due to experimental error. However, the force (on the order of \( 10^{-32} \) to \( 10^{-24} \) N) and resulting drift velocity (0.005 mm/s to 80 mm/s) are sufficient to establish photophoresis as a possible factor in the behavior of dust aggregates with radii of a few micrometers in PPDs.

Index Terms—aggregates, astrophysics

I. INTRODUCTION

Observations of Mercury and rocky exoplanets close to their stars, notably CoRoT-7b and Kepler-10b, indicate that these inner planets tend to be denser than outer planets in similar systems [1]. Mercury, for instance, has an average density of 5300 kg/m\(^3\), significantly greater than Earth’s average density of 4100 kg/m\(^3\) or Mars’ average density of 3800 kg/m\(^3\) [2]. This indicates that Mercury and other innermost planets are comparatively rich in metals [1], which suggests that during the early stages of planetary formation, a mechanism exists to sort the dust in a PPD by composition, moving silicates outward but not affecting metal grains.

The photophoretic force, which occurs due to the interactions of gas particles with an unevenly heated dust grain, is an excellent candidate for this sorting mechanism [1], [3]. This long-studied phenomenon, which has been extensively described elsewhere (for example, [4], [5], [6], [7]), was proposed as a factor in astrophysical environments only in 2005 [3]. Since then, however, it has been suggested as an explanation for the concentration of particular sizes, ages, and compositions of chondrules in asteroids and similar bodies [8] and for the formation of almost dust-free voids in PPDs [9]. In addition, recent experimental work examined the photophoretic force on aggregates and chondrules in laboratory and microgravity conditions and found that it produced a significant acceleration of the aggregates [7]. In view of these experiments, it is logical to assume that photophoresis may play a role in the sorting of dust in a PPD.

The photophoretic force arises from a temperature gradient across a grain. This gradient may develop if the radiation from a young star heats one side of the grain without heating the other. The gradient can form even if the particle is rotating, provided that the rotation is slow enough for the gradient to move across the grain, which is generally the case in a PPD [9]. After this gradient forms, the photophoretic force is directly caused by the collisions of gas particles with the dust grain. These gas particles collide from all directions with velocities corresponding to the ambient temperature. Some of the gas is adsorbed and heats to the surface temperature before rebounding again at a speed given by

\[
v_{\text{rms}} = \sqrt{\frac{3RT}{M_m} \left(1 + \frac{2\mu R}{M_m} \right)}
\]

with \( v_{\text{rms}} \) the root-mean-square speed of the gas particles, \( R \) the ideal gas constant, \( T \) the surface temperature in Kelvin, and \( M_m \) the molar mass of the gas, in kilograms. Since this speed depends on the surface temperature of the collision point, gas rebounds from the hotter side with a greater velocity than from the cold side. By the conservation of momentum, this creates a net force on the dust grain, accelerating it away from its heated side, and thus (usually) away from the light source [5].

Since the photophoretic force depends on the difference in velocity of the rebounding gas particles, and thus on the temperature difference across the grain, it is an ideal mechanism for sorting dust in a PPD. Silicates, with comparatively low thermal conductivity, experience a stronger photophoretic force than metals. Thus, photophoresis could sort the compounds in a PPD such that metals remained near a star, while silicates moved outward [1]. As the dust coagulates to aggregates and then planetesimals, eventually forming planets [10], this sorting effect could produce metal-rich inner planets and rockier outer planets [1].

Many studies have already examined the photophoretic force on spheres and chondrules. Most theoretical treatments, such as those analyzing the photophoretic force at different Knudsen numbers [4] or the effect of differences in the grain’s surface properties [6], have assumed spherical monomers. Other studies work with irregular chondrules, but use radii of mm, rather than the \( \mu \text{m}-\text{scale} \) of early dust aggregates. In [8], the photophoretic force was found to be several orders of magnitude larger than the other main forces in a solar nebula.
II. METHODS

A. Numerical Code

This simulation is based on the OML_LOS (Orbital Motion Limited-Line of Sight) code, which has been used to model the charging in various plasma environments [12], [13] of aggregates built from monomers of varying sizes [11] and shapes [14]. The flux of incoming gas particles is modeled in a manner analogous to that used to find the current density of charged plasma particles to the surface of the grains [12], [13], [15]. Gas molecules approaching the surface are assumed to move on straight-line paths along vectors which are not blocked by other monomers within the aggregate (open lines of sight, LOS). The number of gas molecules impacting a surface per unit area per unit time is given by the flux, \( I \)

\[
I = n \int_0^\infty v \cos \alpha f(v) dv \int_0^{2\pi} d\phi \int_{-\pi/2}^{\pi/2} d\theta
\]

where \( n \) is the number density of the gas, \( v \) is the velocity of a gas molecule, \( \cos \alpha \) is the component of the velocity normal to the surface, and \( f(v) \) is the Maxwellian velocity distribution

\[
f(v) = \frac{1}{\sqrt{2\pi kT}} v^{3/2} e^{-m v^2 / 2kT}
\]

Here \( m \) is the mass of the gas molecule, \( k \) is the Boltzmann constant, and \( T \) is the temperature of the gas. 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

\[
I = n \int_0^\infty \left( \frac{m}{2\pi kT} \right)^{3/2} v^3 \exp \left( -\frac{m v^2}{2kT} \right) dv \int_0^{2\pi} d\phi \int_{-\pi/2}^{\pi/2} d\theta \cos \alpha d\Omega.
\]

Performing the integration over \( \phi \), (3) becomes

\[
I = n \left( \frac{kT}{2\pi^3 m} \right)^{1/2} \cdot \text{LOS_factor}.
\]

The integral \( \int \cos \alpha d\Omega \), the LOS_factor, depends on the open lines of sight at the surface. For points on an isolated sphere, no lines of sight are blocked except by the monomer itself, so the limits for the angular integration are \( 0 \leq \phi \leq \pi/2 \) and \( 0 \leq \theta \leq 2\pi \) and \( \text{LOS_factor} = \pi \) for all points on the surface. However, points on the surface of an aggregate (as illustrated in Figure 1 [13]) may have lines of sight which are blocked by other monomers within the aggregate. Thus the LOS_factor must be calculated numerically. The code generates points on the surface of each monomer which define patches of approximately equal area (up to 10,000 patches total), and at each point checks 1024 test lines of sight to see if they are open or blocked. The open directions are then considered in the summation that approximates the integral over \( d\Omega \). Details of the method are given in [13].

The aggregates used in this simulation consist of collections of spherical dust grains. One population of aggregates were created from monodisperse spheres with radii of 1.7 \( \mu m \), while the second population used polydisperse spheres with radii from 0.5 to 10 \( \mu m \) and a size distribution determined by \( n(a)da = a'^2 da \), with \( n(a)da \) the number of particles with a radius between \( a \) and \( a + da \) and \( \gamma = 3.5 \). The particles were assumed to be silicate and assigned a temperature gradient of 10^4 K/m based on [6]. For comparison purposes, the photophoretic force was also calculated for individual spheres with radii from 0.6896 \( \mu m \) to 28.25 \( \mu m \) (the range of equivalent radii for the polydisperse aggregates) and 3.2209 \( \mu m \) to 47.701 \( \mu m \) for the monodisperse aggregates.

B. Temperature Gradient

Aggregates do not develop a uniform temperature gradient across their component monomers. The simulation assumes a light source along a given direction. Each point is checked to find whether the illumination direction is blocked; the light flux to an open point is calculated by

\[
\Phi_p = \mathbf{n} \cdot \mathbf{\hat{x}} \cdot A
\]

Fig. 1 a) LOS approximation for four points on the surface of a monomer within an aggregate. The shaded areas indicate clear lines of sight, which permit incoming flux, while the other possible angles are blocked by other monomers b) Test directions for the LOS test. Those marked \( t_{1,1} \), etc, are unit vectors defined relative to the monomer's center, C, while those marked \( t' \) are test directions from the center of patch \( m_1 \). (radiation pressure, Poynting-Robertson drag, and the Yarkovsky effect), giving drift velocities on the order of \( 10^{-1} \) m/s. Similarly, [7] studied photophoresis on aggregates and chondrules in drop-tower experiments, finding aggregate accelerations of mm/s^2. Finally, [1] analyzed spherical monomers to find drift velocities of 0.3 mm/s for metal grains compared to 15 mm/s for silicates, establishing photophoresis as a possible sorting mechanism in PPDs.

This study focuses on micrometer-sized dust aggregates. A numerical simulation is used to examine the photophoretic force on irregular aggregates built from spherical monomers. These behave differently from spherical particles in two significant ways. First, since it is assumed that there is little or no heat transfer between the monomers [3] and since one monomer may shadow another, the temperature gradient across the aggregate is irregular. Second, gas particles rebounding from the surface may collide with other areas of the aggregate. Simulating the gas flux to the aggregate and these unique aspects (temperature gradient and gas rebounds) was the main challenge in this numerical simulation, described in Section II. Results follow in Section III; Section IV presents a discussion of the results, while Section V offers a conclusion and recommendations for future work.
where $\vec{n}$ is the unit normal to the surface at that point, $\vec{x}$ is the illumination direction, and $A$ is the area of the patch defined by that point. The total flux to the $i^{th}$ monomer is found by summing over all the patches: $\Phi_i = \sum \Phi_p$

The flux, as well as other factors, is used to define the temperature gradient across the aggregate in three steps. First, an average temperature for each monomer is determined based on the fraction of its surface which is illuminated

$$\bar{T}_i = T + \left( \frac{\Phi_i}{\Phi_{\text{max}}} - 0.5 \right) r_{i,\text{max}} \Phi_i x_{p,\text{max}} \Delta T$$

where $\bar{T}_i$ is the scaled average temperature of each monomer, $T$ is the original average temperature (600 K here), $\frac{\Phi_i}{\Phi_{\text{max}}}$ is the ratio between the integral over $\Omega$ in the light’s direction of each monomer and that of a fully illuminated sphere, $\Phi_i$ is the integral over $\Omega$ in the light’s direction for the monomer, $x_{p,\text{max}}$ is the (unit-vector) coordinate of the point on the sphere’s surface with the highest temperature, $r_{i,\text{max}}$ is the maximum radius of the monomers in the aggregate, and $\Delta T$ is the temperature gradient across the dust. The surface temperature of each illuminated point is then found from

$$T_p = \bar{T}_i + r_{i,\text{max}} \Phi_p x_p \Delta T$$

with the variables defined as above. The surface temperature of each shadowed point is given by

$$T_p = \bar{T}_i + r_{i,\text{max}} \Phi_p x_{sh} \Delta T$$

where $x_{sh}$ is the coordinate of the point defined relative to the coordinate in the light’s direction of the last illuminated point on the monomer and the other variables are defined as above.

A sample temperature gradient is shown in Fig. 2.

C. Gas Rebounds

With an aggregate’s irregular surface geometry, gas molecules leaving the surface in a random direction may escape into space or collide with another part of the aggregate. Here it is assumed that all gas particles which collide with the aggregate equilibrate with the local surface temperature before being ejected, effectively setting the “energy accommodation coefficient” equal to 1, as in [1], [7], [9]. Gas particles are allowed to leave the surface along any of the 1024 test directions not blocked by the monomer itself. If the rebound direction is blocked by another monomer in the aggregate, the flux from the blocked point is added to the gas flux to the blocking point, a new rebound direction is selected for this point, and the process repeats until an open direction is selected. If it is not blocked, the momentum transfer from the gas to the aggregate due to this rebound is calculated and added to the total momentum transfer.

Momentum transfer from the gas to the aggregate occurs at every collision and rebound; however, the momentum transfer to the aggregate from a rebound is canceled if the gas particle collides with another monomer. 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 momentum from the incoming particles at each rebound, for each point, is calculated by

$$\left( \frac{P_{\text{in}}}{\Delta t} \right)_p = I_p m v_g A_p$$

while the momentum from particles rebounding into space is

$$\left( \frac{P_{\text{out}}}{\Delta t} \right)_p = I_p m v_s A_p$$

In both equations, $m$ is the mass of the gas particle, $I_p$ the flux at point $p$ calculated by (4), $A_p$ the area of the patch surrounding that point, and $v$ the root-mean-square velocity from (1), with $T$ the average temperature of the gas for $v_g$ and the temperature of the surface at the rebound point for $v_s$. To convert these magnitudes into vector expressions, they are multiplied by the average open LOS for each point for the incoming momentum, and the chosen rebound directions for the outgoing momentum. Gas rebounds continue until 99.99% of the particles have rebounded, at which point the remaining 0.01% of particles are assumed to rebound along the average open LOS. The total change in momentum per unit time, and thus the magnitude of the force on each patch, is given by

$$F_p = \left( \frac{P_{\text{in}}}{\Delta t} \right)_p + \left( \frac{P_{\text{out}}}{\Delta t} \right)_p$$

The total force on the grain is found by taking the vector sum of the force on each of the patches.

The drift velocity of the aggregate is calculated using

$$v_{\text{drift}} = \frac{F}{m_d \cdot \tau}$$

with $\tau$, the gas grain coupling time, given by [16]

$$\tau = \gamma \frac{m_d}{\sigma \rho_g v_g}$$

with $m_d$ the mass of the dust aggregate, $\sigma$ its average cross-sectional area, $\rho_g$ the gas density, $v_g$ its velocity, and $\gamma$
exponentially determined (in [16]) to be 0.68. Since the random rebound directions strongly affect the resultant forces and velocities, the simulation was run 1,000 times for each aggregate and the forces and velocities were averaged.

Due to irregularities in the aggregate structure, the rebounding gas particles produce significant forces even without a temperature gradient across the aggregate. The magnitudes of these forces—on the order of $10^{-20}$ N—are reasonable for gas drag [17], [18], [19]. To differentiate the drag force on the aggregate from the photophoretic force, on each trial the surface temperature and resultant rebound velocity and momentum transfer for the gas were calculated with the temperature gradient set to 0 K/m as well as with the gradient set to $10^4$ K/m. Since the same rebound directions were used in each calculation, the difference between the results represents the photophoretic force (Fig. 3).

The current code neglects any torque and subsequent rotations caused by gas drag, collisions between dust particles, and thermal forces, since earlier experiments found that for most particles greater than 1 μm in size, these rotations are quickly damped by the surrounding gas, happen slowly enough that a temperature gradient can form, or occur only along the radial direction and thus leave the gradient unaffected [3]. In experiments with photophoresis on ice crystals in a near-vacuum, Eymeren & Wurm [20] found that the ice aggregates rotated only along radial axes, parallel to the direction of illumination, probably due to the fact that the directions of illumination and gravity were the same, allowing the particles to reach equilibrium between gravity and the photophoretic force.

D. Analysis Techniques: Compactness Factor

The averaged force and velocity were analyzed as functions of the aggregates’ physical parameters, such as mass, equivalent radius, and compactness factor. Compactness factor describes the “fluffiness” of the aggregate [13], [15]. It is calculated by finding the aggregate’s average projected cross-sectional area. A circle of equivalent area, with equivalent radius $R_e$, is then defined. The compactness factor is the volume of the aggregate, calculated as the sum of the volumes of the individual monomers, divided by the volume of a sphere with radius $R_e$.

$$\phi = \frac{\sum_{i=1}^{N} r_i^3}{R_e^3}$$

with $N$ the number of monomers and $r_i$ their individual radii [13]. A compactness factor approaching 0 indicates an open, fluffy aggregate, while a compactness factor near 1 indicates a very compact, spherical aggregate.

III. Results

A. Monodisperse Aggregates

The monodisperse aggregates contained 2 to 2179 monomers, with compactness factors from 0.0945 to 1.3869 (the values greater than 1 occurred due to errors when analyzing the smallest aggregates). The magnitude of the x-component of the photophoretic force ranged from $1.0714 \times 10^{-20}$ N to $4.2039 \times 10^{-25}$ N (due to the direction of the temperature gradient, the y and z components are negligible here, though they will be discussed later), with corresponding drift velocities of $6.7224 \times 10^{-6}$ m/s to 0.0098 m/s. In comparison, the x-force on spheres of equivalent radii ranged from $1.2216 \times 10^{-27}$ N to $3.9672 \times 10^{-24}$ N (with drift velocities of 0.0056 m/s to 0.0831 m/s), while the force on spheres of equivalent mass was from $1.4369 \times 10^{-28}$ N to $1.5655 \times 10^{-25}$ N (with drift velocities of 0.0028 m/s to 0.0283 m/s). For clarity, in all figures, all components of the forces and drift velocities of the aggregates and spheres were normalized by the magnitude of the force and velocity on a single monomer with radius of 1.7 μm (1.7963 $\times 10^{-28}$ N and 0.0030 m/s, respectively), while the mass or radii were normalized by the mass (5.1449 $\times 10^{-10}$ kg) and radius of the monomer.

When force and velocity were plotted against radius (Fig. 4 and Fig. 7), the force on the aggregates was orders of magnitude smaller than the force on the spheres of comparable radius, a trend which extended to the velocities. When the force and velocity were plotted against mass (Fig. 6, Fig. 5), however, the aggregates’ force was slightly greater than the force on spheres of similar mass (although due to differences in cross-sectional area, the resultant drift velocity of the aggregates was less than the drift velocity of the spheres).

**Fig. 3** Photophoretic force on an aggregate, with rebounds only along the average open directions. The green arrows indicate the difference between the momentum of the rebounding particles with a temperature gradient present and the momentum without a temperature gradient, which is the photophoretic force. Note that the temperature difference across the aggregate was increased by modifying (7) and that the actual photophoretic force is directed in the opposite direction, pushing the aggregate away from the illuminated side; however, the arrows are reversed and directed outward from the surface for clarity.
The force and drift velocity for the aggregates, normalized by the force and drift velocity of a monodisperse monomer, were also plotted against the compactness factor (Fig. 10, Fig. 9). The photophoretic force approached 0 as the compactness factor approached 1, indicating a dense, spherical aggregate (although due to errors in the code, some aggregates were assigned compactness factors greater than 1).

B. Polydisperse Aggregates

Polydisperse aggregates contained from 2 to 1376 monomers. The magnitude of the x-component of the photophoretic force ranges from $8.2166 \times 10^{-33}$ N to $1.8930 \times 10^{-25}$ N, with a resultant velocity from $4.4374 \times 10^{-7}$ m/s to 0.0615 m/s. A few negative values arise from the smallest and most irregular aggregates, indicating a force toward the light, but the force and velocity of nearly all aggregates is directed away from the light source.

In comparison, the magnitude of the force on the spheres with equivalent radii runs from $1.0945 \times 10^{-29}$ N to $8.2414 \times 10^{-25}$ N, with resultant velocities from 0.0012 m/s to 0.0492 m/s. The spheres with equivalent masses have slightly smaller radii than the aggregates; thus, their force ranges from $1.0184 \times 10^{-29}$ N to $2.3225 \times 10^{-25}$ N with resulting velocities from 0.0011 m/s to 0.0323 m/s.

For clarity, all components of the force and velocity of the aggregates and the spheres are scaled by the magnitude of the force on an average monodisperse monomer (1.65 μm). These magnitudes were $1.6424 \times 10^{-28}$ N and 0.0029 m/s, respectively.

In Fig. 4, photophoretic force vs. radius for the monodisperse aggregates and the spheres. The spheres’ force is dependent on the square of the radius, while the aggregates’ demonstrates a similar trend but is much smaller in magnitude. Both forces are scaled by the force on an average monodisperse monomer.

In Fig. 5, photophoretic velocity vs. mass for the monodisperse aggregates and the spheres. The spheres’ velocity is dependent on the square root of the mass; the aggregates’ demonstrates a similar trend but is smaller in magnitude. Both velocities are scaled by the velocity of an average monodisperse monomer.

In Fig. 6, photophoretic force vs. mass for the monodisperse aggregates and the spheres. Both forces are linearly dependent on the mass, and similar, although the aggregate force is slightly greater than the force on the spheres. Both are scaled by the force on an average monodisperse monomer.

In Fig. 7, photophoretic velocity vs. radius for the monodisperse aggregates and the spheres. The spheres’ velocity is linearly dependent on the radius, while the aggregates’ demonstrates a similar trend but is much smaller in magnitude. Both velocities are scaled by the velocity of an average monodisperse monomer.
addition, the mass and radius of the aggregates and spheres are scaled by the mass and radius of this average polydisperse sphere ($4.7041 \times 10^{-14}$ kg and 1.65 μm).

The force and velocity of the aggregates remained consistent whether plotted against radius (Fig. 11, Fig. 8) or mass (Fig. 15, Fig. 14); they followed the spheres’ trends (with force quadratically dependent on radius and linearly dependent on mass), but were lower than the spheres in all cases. Their trends proved extremely similar to the monodisperse force and velocity; however, in the polydisperse case the aggregates’ force and velocity were closer to those of the spheres of equivalent radius, and the force when plotted against mass was lower than the force on the spheres. The normalized force and velocity for the aggregates approached 0 as the compactness factor approached 1 (Fig. 12, Fig. 13).

IV. DISCUSSION

A. Comparison with Spheres

The aggregates of both size distributions behaved similarly to each other, as predicted. The overall trends in the force and drift velocity of the aggregates were similar to those of the spheres, though the irregular aggregate shapes and random gas rebounds increased the error in the aggregate data.

The maximum force and velocity for the spheres when plotted with respect to radius was significantly greater than the spheres’ maximum force and velocity when plotted with respect to mass, although the force and velocity of the aggregate remained consistent. This occurred because the range of the x-axis was determined by the aggregates. The
spheres with equivalent radii to the aggregates had significantly higher masses than the aggregates. Thus, the plots with respect to radius considered a wider range of sphere masses, resulting in an increased photophoretic force on the spheres. Spheres with equivalent radii and greater masses experienced a far stronger force than the aggregates, while spheres with smaller radii and equivalent masses experienced roughly the same photophoretic force as the aggregates.

The polydisperse aggregates’ force in the y-direction is less easily explained. The temperature gradient was directed along the x-axis, and although asymmetry in the aggregates might produce some force in the y and z directions, the currently observed force in the y-direction is only one order of magnitude smaller than the force in the x-direction, while the z-direction experiences essentially no force.

The fact that the force and velocities of the aggregates were consistently lower than those of the spheres is also unexpected. As the aggregates should be less thermally conductive than spheres, due to little heat transfer between the monomers [3], it was predicted that the temperature difference across the aggregates would be greater than the difference across a sphere, and this would produce a greater force on the aggregates than on the spheres. Errors in the code are a probable cause of this discrepancy. The temperature gradient across an aggregate has not been extensively studied. In addition, the number of points generated on each aggregate where gas particles may collide was limited to 10,000 points, which may not have been adequate for the larger aggregates. Both of these error sources may be addressed in future work.

B. Compactness Factor

The force on the aggregate decreased with compactness factor because a higher compactness factor indicates a smaller
ratio between surface area and volume; aggregates with high compactness factor have relatively little surface area for the gas to collide. Since compactness factor considers both the equivalent radius of an aggregate and (indirectly, through volume) its mass, it may prove an effective method of characterizing the photophoretic force on an aggregate, which is strongly affected by both of these factors.

C. Comparison with Previous Work

The photophoretic force and drift velocity observed in this experiment is comparable to previous work on aggregates. In [7], for instance, the photophoretic force on larger dust aggregates was experimentally studied. For dust aggregates, the acceleration ranged from 1.490 ± 0.198 mm/s² to 200.780 ± 4.774 mm/s², although the diameters of these aggregates ranged from 1.37 to 1.93 mm ± 10%, significantly larger than the aggregates analyzed in the current study.

V. CONCLUSION AND FUTURE WORK

The photophoretic force on micrometer-sized dust aggregates has a significant influence on their behavior. Although the force on aggregates may be less than the force on spheres of comparable mass or radius, the force is undoubtedly sufficient to produce drift velocities on the orders of mm/s in silicate aggregates. Combined with previous work on single particles and larger dust aggregates, this suggests that photophoresis may be a mechanism for the sorting of dust by composition in a protoplanetary disk.

This simulation may be modified significantly in future studies. Theoretical studies have already created more complex calculations of the heat source function, and thus temperature gradient, across an aggregate [21]. Although some studies suggest that due to the small size of the gas particles and the differences in accommodation coefficients, heat transfer to the gas has no significant effect on the gradient [3], it may be necessary to consider heat transfer from the gas to the colder areas of the aggregate. Finally, future versions of the code should analyze gradients along different axes to differentiate between the effects of the aggregate shape and the temperature gradient.

Modeling aggregates with irregularly shaped monomers would provide more detailed information on the photophoretic force. Experimental work, such as that being performed by Wurm et al. [7], [20], may also guide future models. This simulation is thus a small element in a broader understanding of the photophoretic force’s effect on dust aggregates.

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REFERENCES


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