Photophoretic Force on Dust Aggregates

Jesse B. Kimery, Lorin S. Matthews, Truell W. Hyde

Center for Astrophysics, Space Physics, and Engineering Research

One Bear Place 97310, Waco, Texas, 76798-7310 USA

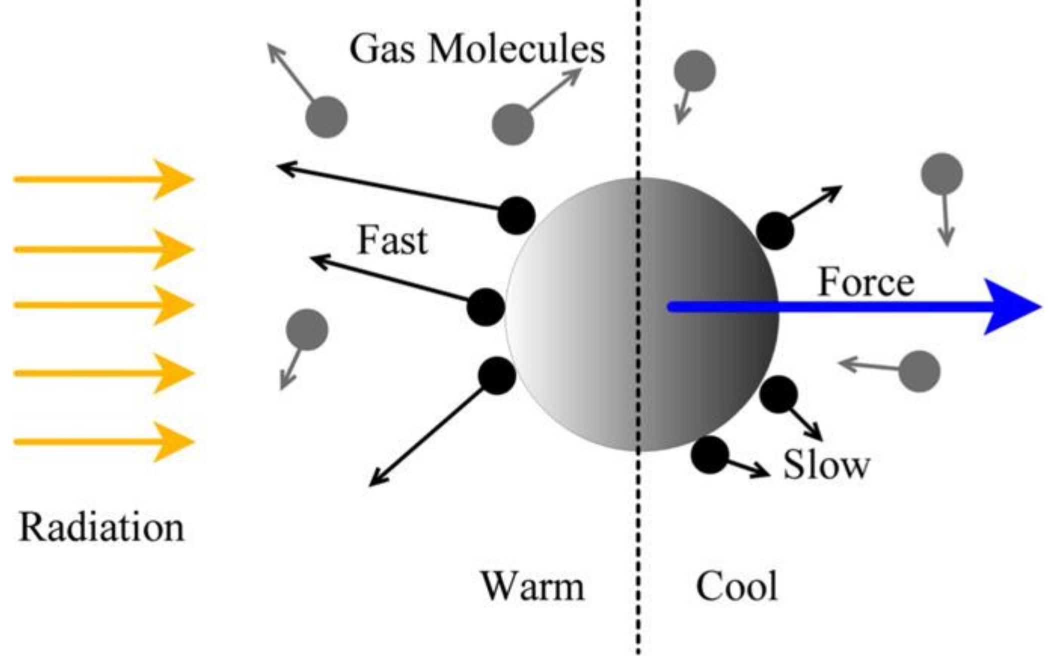
www.baylor.edu/CASPER

Photophoresis in Protoplanetary Disks

Observations of inner planets in our own and other solar systems indicate that relative density of the planets decreases with distance from the sun [1]. This suggests that some force may exist which sorts the 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].

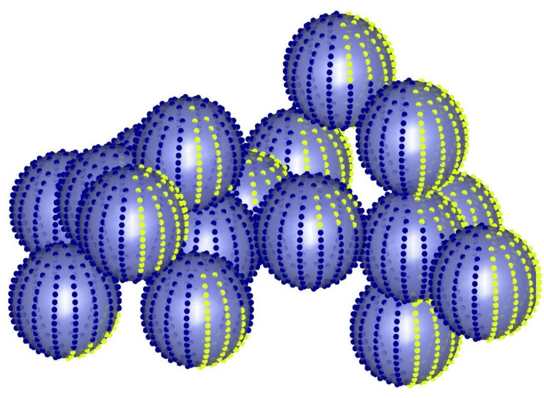
Photophoretic Force

- Partial illumination creates temperature gradient across dust
- Surface temperature of dust differs from temperature of surrounding dilute gas
- Gas rebounds with greater speed from heated surface, rebounds with slower speed from cool surface
- Net transfer of momentum in general pushes dust grain away from the direction of illumination
- Silicates have lower thermal conductivity than metallic grains, and thus experience a larger photophoretic force, which may provide a sorting mechanism [1]
- **How does the photophoretic force affect irregular μm-sized aggregates?**



Numerical Model

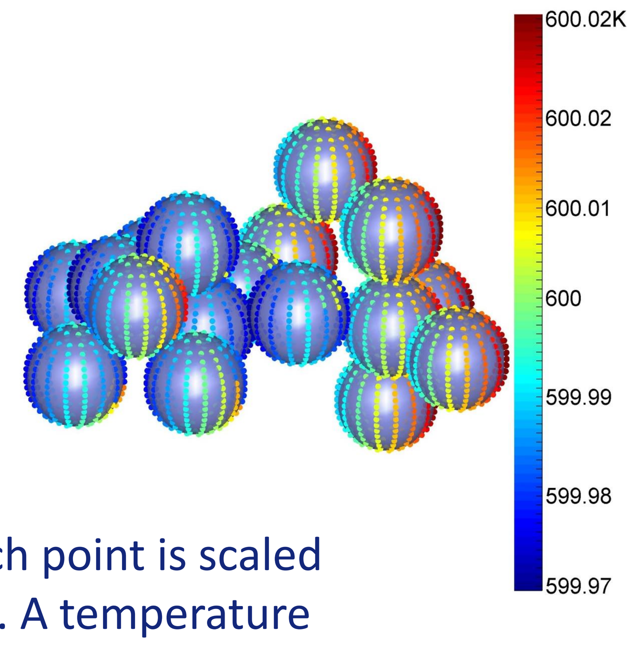
A numerical model based on the lines of sight (LOS) to points on the aggregate surface [3] was used to determine the illumination, estimate the temperature gradient, and calculate the photophoretic force and resultant drift velocity.



Illumination

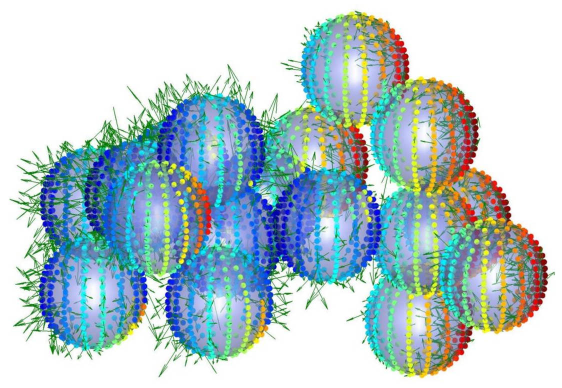
Light source from one direction. The total flux to each point on surface is calculated

Temperature



The temperature at each point is scaled by the illumination flux. A temperature gradient of 10^4 K/m is used to set the temperature of a shadowed point.

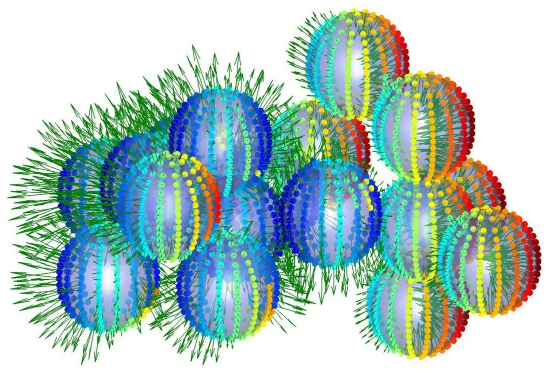
Momentum Transfer



Open LOS to a given point are used to determine the total gas flux to that point. Gas molecules are incident along open lines of sight, accommodate to the local surface temperature, and rebound in random directions.

Gas molecules which rebound and hit another point on the aggregate surface accommodate to the local surface temperature, and a new random rebound direction is chosen. Process repeats until 99.9% of gas molecules have rebounded along an open LOS.

This process is repeated multiple (70-80) times to determine the average direction of the force.



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; <r> = 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.

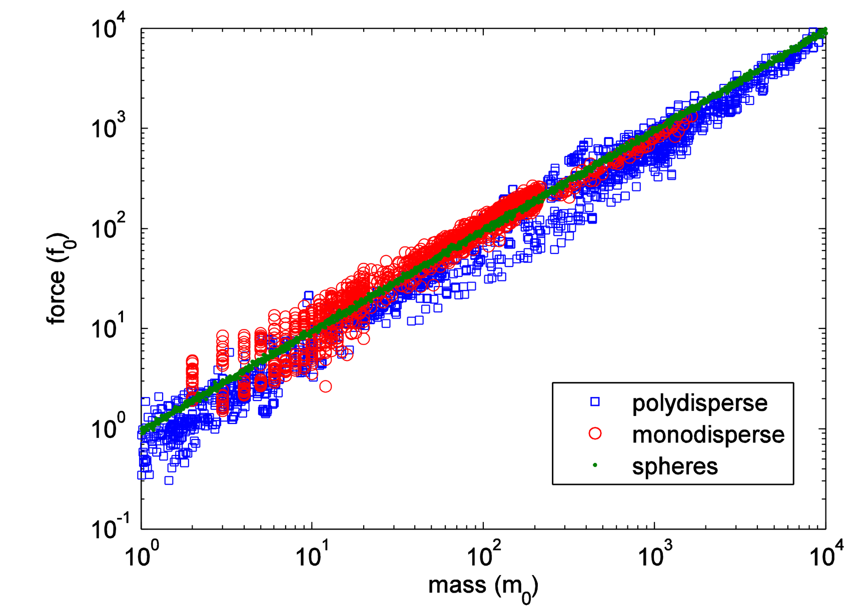
The drift velocity of the aggregate is calculated by

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

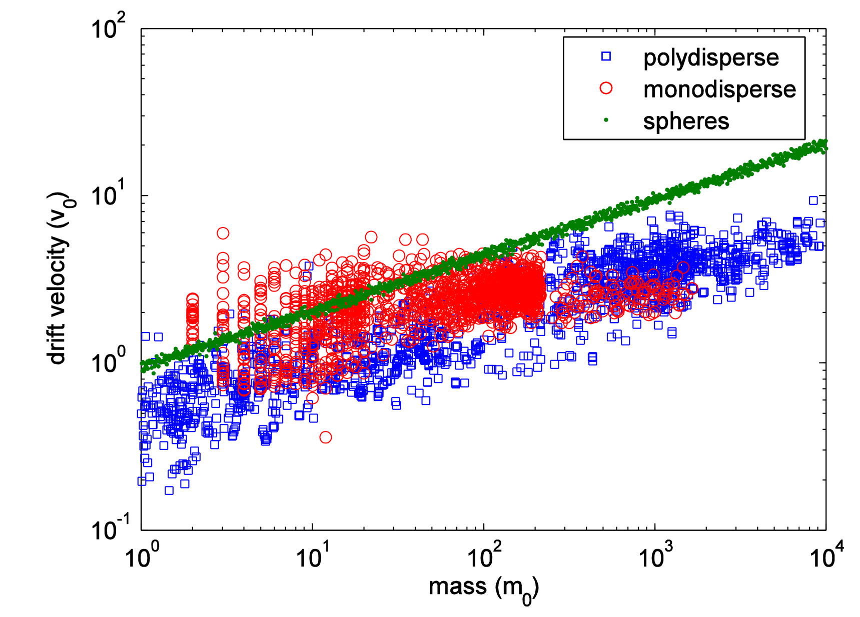
with τ, the gas grain coupling time, given by [4]

$$\tau = \gamma \frac{m_d}{\sigma} \frac{1}{\rho_g v_g}$$

with m_d the mass of the dust aggregate, σ its average cross-sectional area calculated as in [3], ρ_g the gas density, and γ experimentally determined to be 0.68 [4].



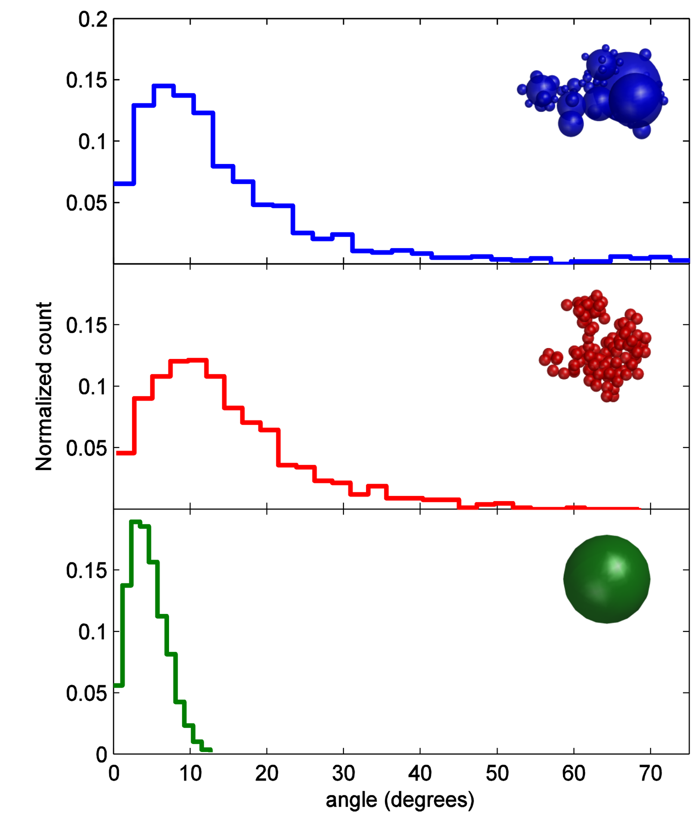
Photophoretic force vs. mass, normalized to the force and mass of a sphere with r = 1.7 μm, $F_0 = 2.83 \times 10^{-28}$ N and $m_0 = 5.14 \times 10^{-14}$ kg.



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, $m_0 = 5.14 \times 10^{-14}$ kg

Direction of Photophoretic Force

Due to the irregularity of the grain surface and the diffusion of the gas through the aggregate, the direction of the photophoretic force can deviate significantly from the direction of illumination.



Conclusion

- Photophoresis significantly impacts aggregates with μm-scale radii in conditions corresponding to a PPD
- Drift velocities range from ~1-50 mm/s, giving a sorting time over a distance of 1 AU of 10 thousand to 5 million years
- Drift velocity not necessarily along direction of illumination

References

[1] Wurm G., Trieloff M., and Rauer H. (2013) *Astrophys J*, 769, 78-84.
[2] Krauss O. and Wurm G. (2005) *Astrophys J*, 630, 1088-1092.
[3] Matthews L. S., Land V., and Hyde T. W., (2012) *Astrophys J*, 744, 397-398.
[4] Blum J., Wurm G., Kempf S., and Henning T., (1996) *Icarus*, 124(2), 441–451

This material is based upon work supported by the National Science Foundation under Grant No. 1002637