# PHOTOPHORETIC STRENGTH ON CHONDRULES: MODEL AND EXPERIMENT.

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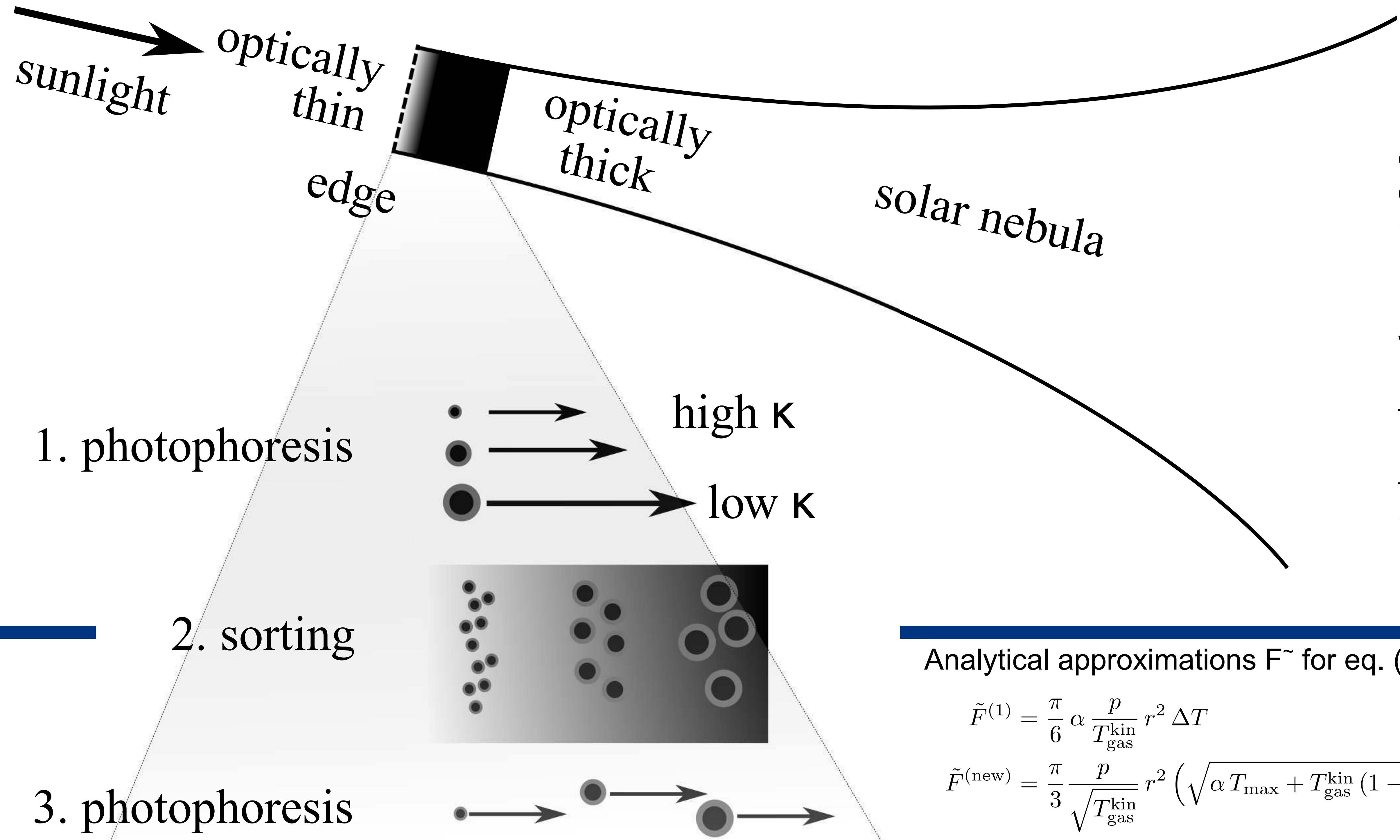

## Introduction

Photophoresis might give an answer to current questions on radial transport and size sorting of chondrules in the solar nebula. Conditions for photophoresis in such a disk are depending on time and place [1].

One location where photophoresis acts is at the outwards moving edge of a protoplanetary disk. In the free molecular regime the force can be expressed by eq. (1).

In [2] steady state photophoretic forces on actual chondrules were numerically modeled, all based on tomographic data.

[3] put emphasis on microgravity experiments at the drop tower in Bremen, Germany. Here, a short summary of both publication shall be given alongside with the presentation of the general solution of the integral equation for the photophoretic force on a particle with star-like domain.

$$\mathbf{F}_{\mathrm{phot}} = -\frac{1}{2} \oint\limits_{S_{\mathrm{par}}} p \left(1 + \sqrt{1 + \alpha \left(\frac{T}{T_{\mathrm{gas}}} - 1\right)}\right) \mathbf{d}\boldsymbol{\sigma} \qquad (1)$$

Analytical approximations F˜ for eq. (1) in terms of macroscopic parameters:

$$\tilde{F}^{(1)} = \frac{\pi}{6}\, \alpha\, \frac{p}{T_{\mathrm{gas}}^{\mathrm{kin}}}\, r^2\, \Delta T$$

$$\tilde{F}^{(\mathrm{new})} = \frac{\pi}{3} \frac{p}{\sqrt{T_{\mathrm{gas}}^{\mathrm{kin}}}}\, r^2 \left(\sqrt{\alpha\, T_{\max} + T_{\mathrm{gas}}^{\mathrm{kin}}\,(1-\alpha)} - \sqrt{\alpha\, T_{\min} + T_{\mathrm{gas}}^{\mathrm{kin}}\,(1-\alpha)}\right)$$

$$\tilde{F}^{(2)} = \frac{\pi}{6}\, \alpha\, \frac{p}{T_{\mathrm{gas}}^{\mathrm{kin}}}\, r^3\, \frac{I}{k}$$

$$\tilde{F}^{(3)} = \frac{\pi}{6}\, \alpha\, \frac{p}{T_{\mathrm{gas}}^{\mathrm{kin}}}\, \frac{r^2\, I}{\frac{k}{r} + 4\sigma \left(\frac{I}{4\sigma} + \left(T_{\mathrm{gas}}^{\mathrm{opt}}\right)^4\right)^{\frac{3}{4}}}$$

$$F_{\mathrm{corr}}^{(3)} = \left(0.7231 - 0.1741 e^{-2.180 \frac{r}{k} \mathrm{W/(m^2\,K)}} + 0.4316 e^{-0.9251\alpha}\right) \tilde{F}^{(3)} \quad (2)$$

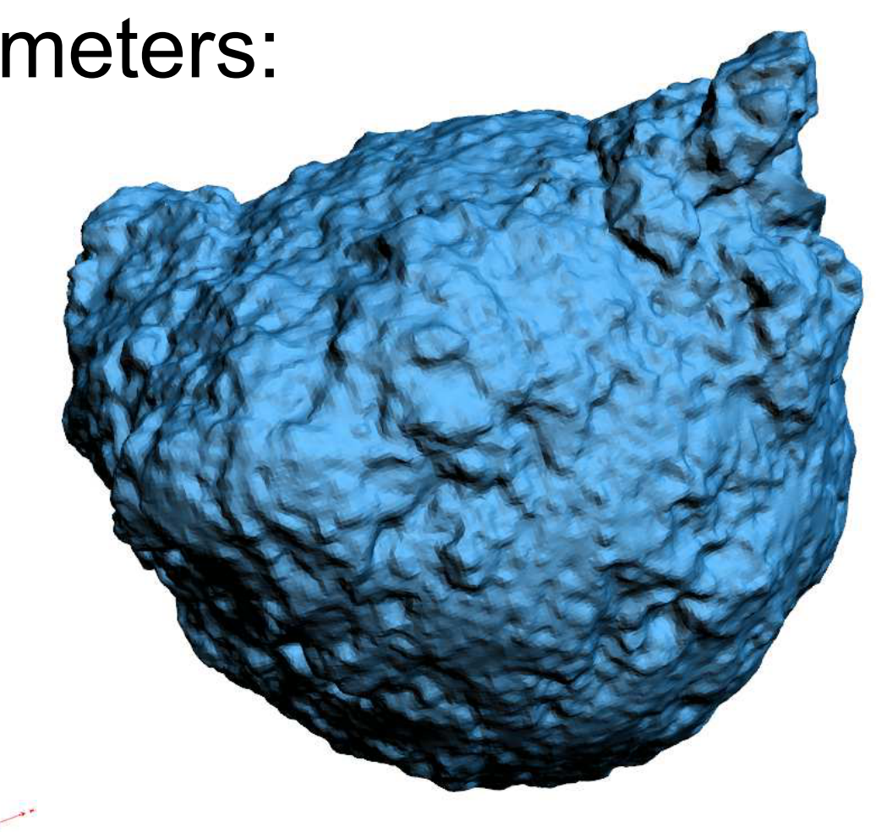

**Fig. 1: Example of a chondrule having a not-perfect spherical shape, but for which the average photophoretic force can be exactly calculated like for spheres by simply taking the radius of a volume equivalent sphere.**

The approximations give the force in direction of illumination. They are only valid for spheres with rotational temperature distribution across the surface, i.e., if a spherical and homogeneous particle is uniformly illuminated. In case of rotating spheres this is already not the case anymore, hence the approximations above can be incorrect.

## Model [2]

For perfectly spherical and homogeneous bodies the photophoretic force is parallel to the incidence of radiation which is eventually heating up the body. As this is not true for non-spherical particles or maybe strongly inhomogeneous spheres, tomographic data of actual chondrules, extracted from Bjurböle meteorite, was used to create a model based on the geometry at a resolution of ca. 5µm/voxel and thermal conductivity collected from mineralogical analysis. Existing approximations for eq. (1) acting on spheres always involve the sphere's radius and sometimes the thermal conductivity (for details, see equations above). To keep these advantageous approximations when extending the description of Photophoresis to non-spherical bodies, the sphere's radius can simply be replaced by the radius of a volume-equivalent sphere and the same approximations now describe mean values or expectation values, respectively (Fig. 2+3).

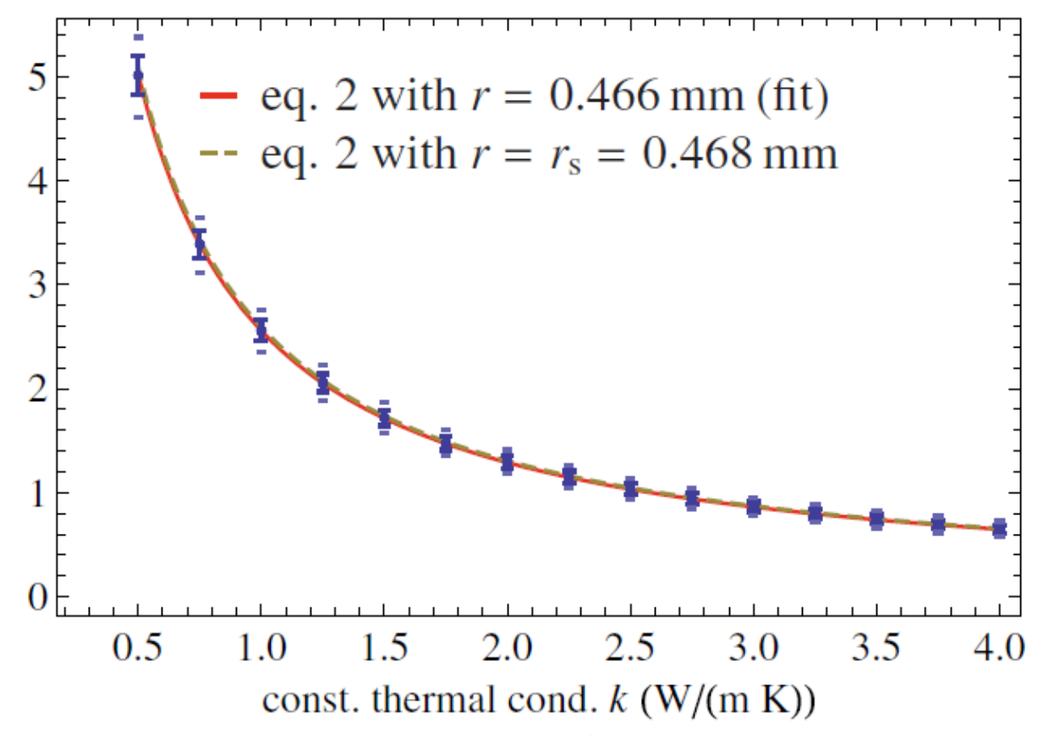

**Fig. 2: F over pressure p for an actual chondrule over constant thermal conductivities k.**

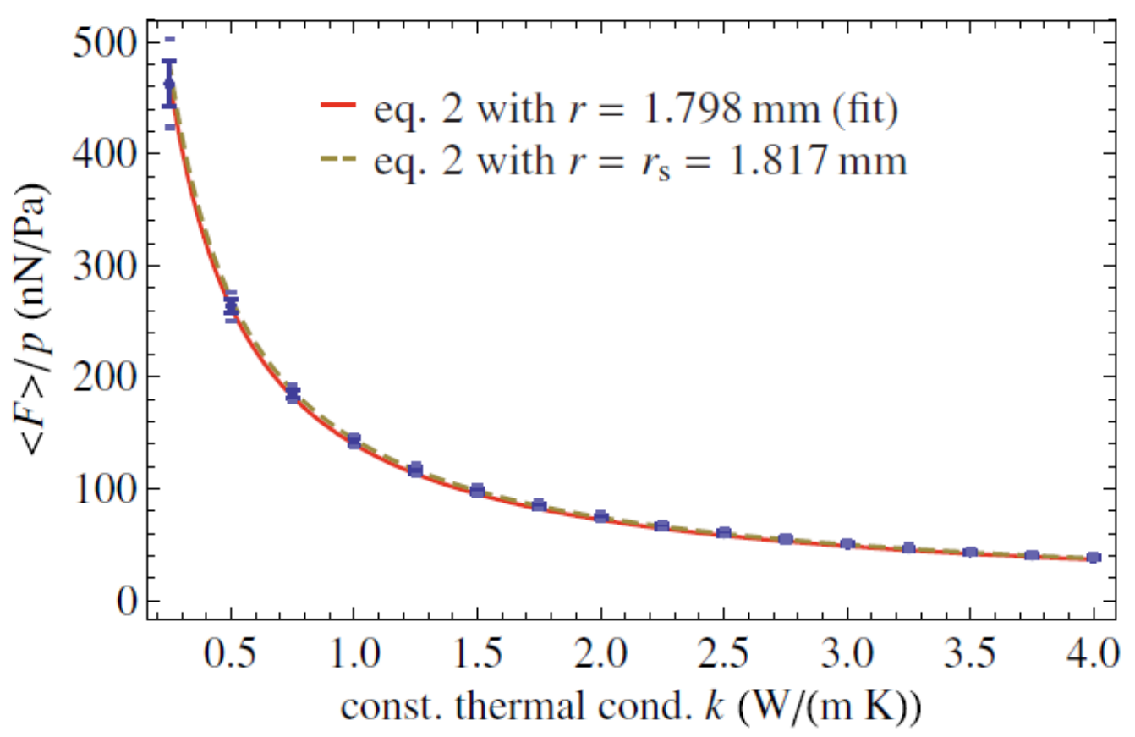

**Fig. 3: F over pressure p for ellipsoid with half-axes (1,2,3)mm for constant thermal conductivities k.**

If the thermal conductivity is unknown, an effective thermal conductivity can be derived by means of methods described in. In the case of two dominant phases in the chondrules, an effective thermal conductivity can be assigned with the help of a two-phase diagram (Fig. 4): by measurement of each volume share in the chondrule (e.g. through X-ray tomography) the effective thermal conductivity is determined.

In the set of investigated chondrules we could see a dependence of the effective thermal conductivity on the chondrule size, which is important for potential sorting and transport scenarios in, e.g., protoplanetary disks (Fig. 5).

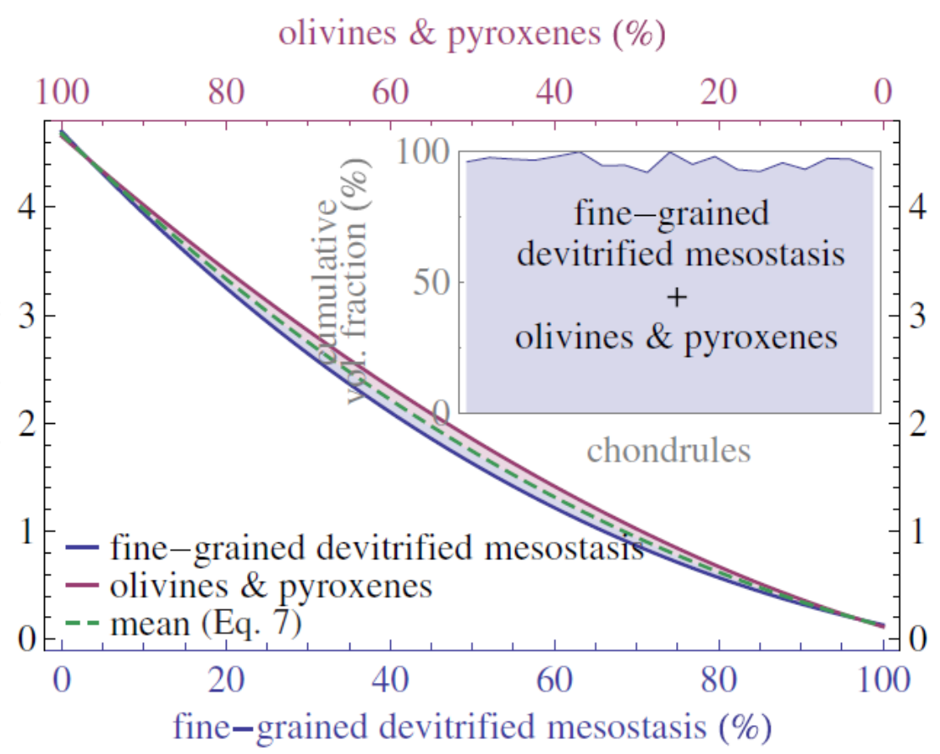

**Fig. 4: Two-phase diagram for a chondrule's effective thermal conductivity k.**

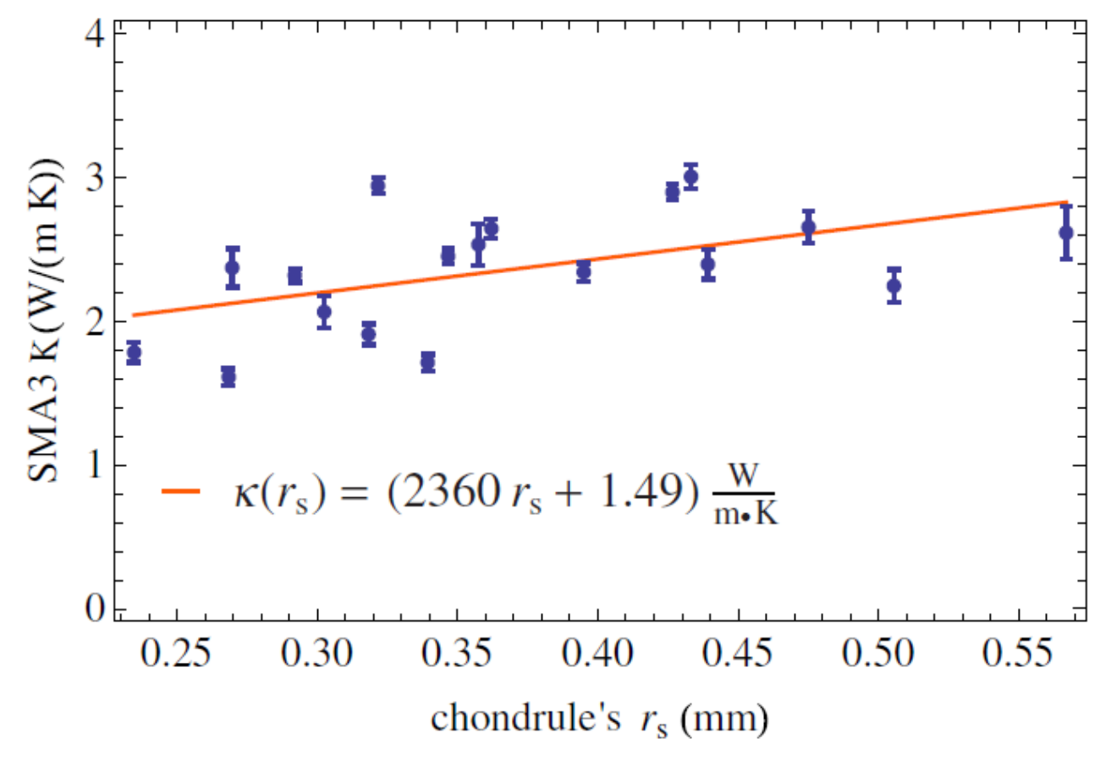

**Fig. 5: Cyclic simple moving average (3rd order) of effective thermal conductivity k for actual chondrules and their volume equivalent radius.**

CONCLUSIONS: The average variation of the absolute value of the photophoretic force over all chondrules is only 4.17%. The deviation between the direction of illumination and the photophoretic force is just 3.0°±1.5°.

## Experiment [3]

Microgravity experiments, carried out at the Bremen (Germany) drop tower, showed strong rotation and reorientation of chondrules, hence numerical studies on rotating spheres were conducted. Overall, the measured values for the photophoretic force deviated from those proposed in steady-state models. We found, that rotation, heat-up, and reorientation after collisions and thus the limited observation time of only 9s can explain those difference. The influence of the angle between irradiation and photophoretic force on rotation frequency as well as its value were discussed in this paper. The photophoretic force during heat-up shows a similar behavior like in the case for rotation. The observation time is crucial for correct measurements as a heat-up (e.g. due to reorientation) has significant influence on the photophoretic force acting on the chondrule; the saturated value/steady-state value for the photophoretic force is much higher than any value measured within the first seconds (Fig. 6).

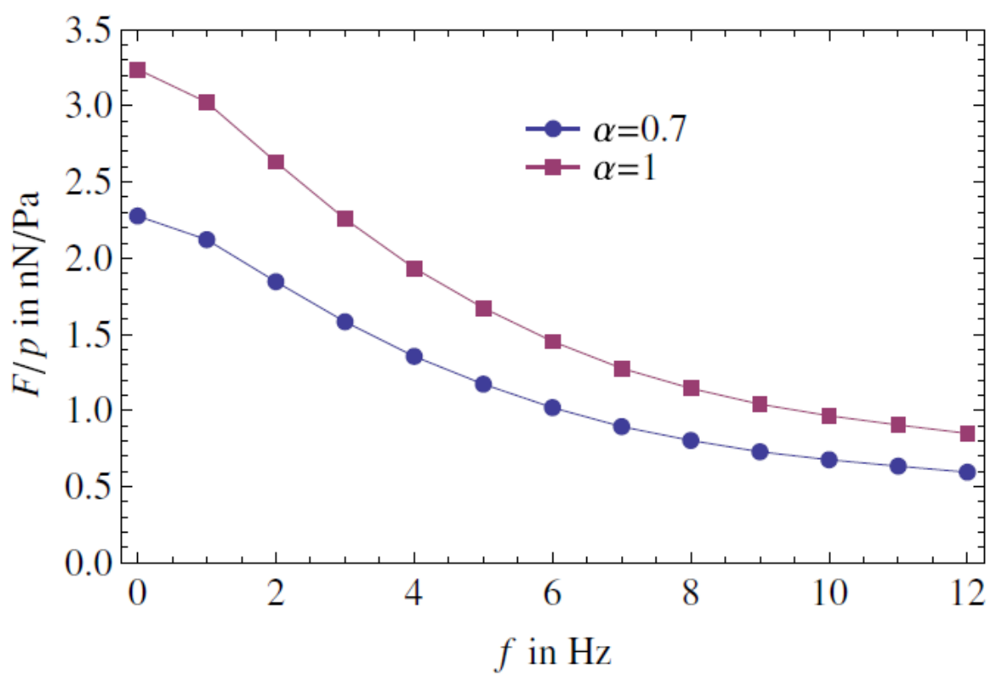

**Fig. 6: Evolution of the photophoretic force with time.**

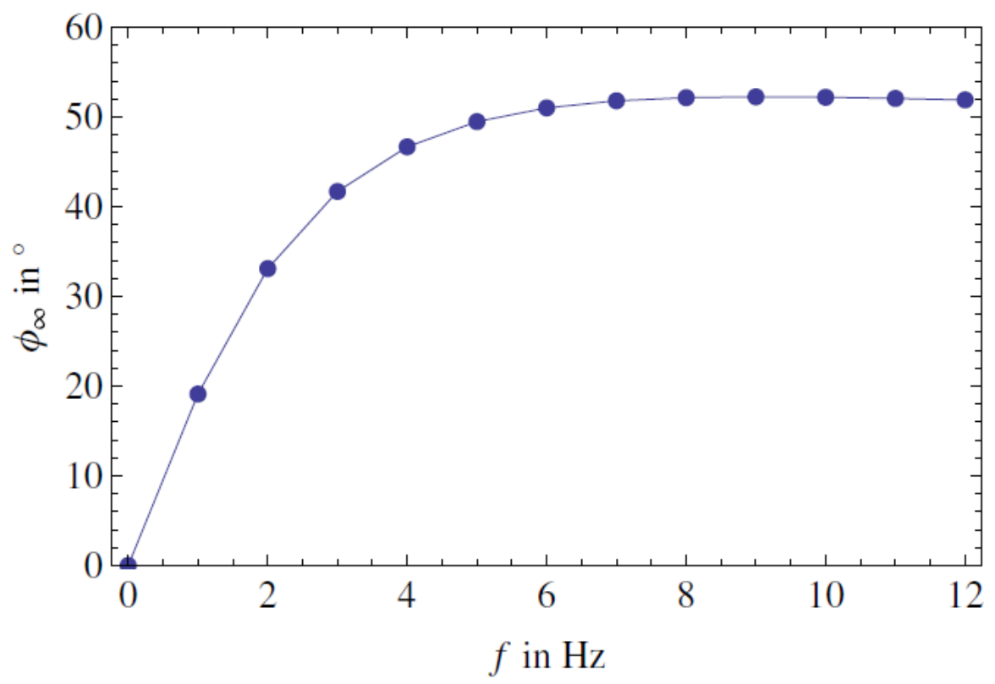

**Fig. 7: Angles between photophoretic force and the direction of incident light for large times.**

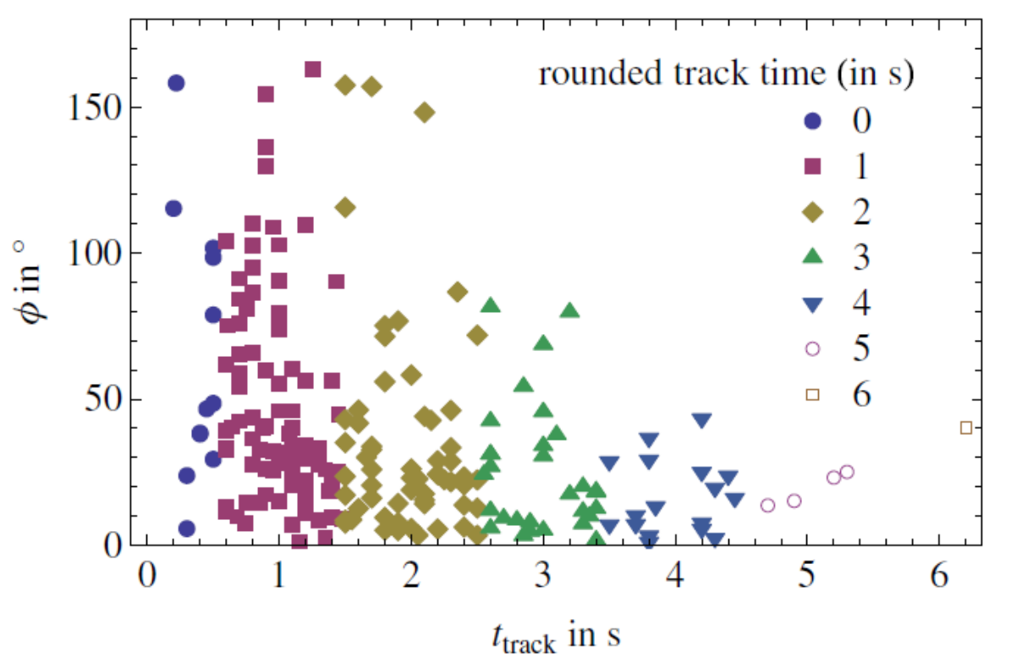

**Fig. 8: Angles between photophoretic force and the direction of incident light for different tracking times.**

The angle between photophoretic force and irradiation direction also has a saturation value, which is reached even faster as the rotation frequency increases. In our studies this saturation value is about 52° (Fig. 7).

The influence of the observation time is shown in Fig. 8. In our experiments an observation time of at least 3.3-3.5s is necessary to yield useful results as only for those measurements the angle is below the theoretical limit of ca 50°. Higher values arise from collisions and reorientation afterwards and the necessity of a new heat-up alongside the irradation direction.

CONCLUSIONS: Experiments show strong deviations from the steady-state numerical models on one magnitude of order which can be explained due to rotation, bouncing and heat-up. Also hints for the Yarkovski and the YORP effect could be seen.

## Outlook: General solution

We derived the general solution of the integral eq. (1). It covers all cases of photophoresis on particles with star-like domains when both, the integrand in (1) and the particle surface are expressed in terms of spherical harmonics. The approximations from above can be derived as special cases, as well as eq. (3), describing the force on spherical particles with an arbitrary temperature field (including the case of rotating chondrules). The general solution is subject for further studies on photophoresis on bodies with star-like domain.

Currently we model the Yarkovski and Yorp effects by means of finite elements method using CAD models of actual chondrules retrieved by X-ray tomography (as already used in [2]). Results will be published soon.

$$\mathbf{F}_{\mathrm{phot}} = \sqrt{\frac{\pi}{3}}\, \frac{p}{\sqrt{T_{\mathrm{gas}}}}\, r^2 \begin{pmatrix} \sqrt{2}\, \Re\left(t_{1,1}^*\right) \\ \sqrt{2}\, \Im\left(t_{1,1}^*\right) \\ -t_{1,0} \end{pmatrix} \qquad (3)$$

**Bibliography**
[1] Wurm, G. et al. 2010. Icarus, 208: 482-491
[2] Loesche et. al. 2013, APJ 778(2), pp. 101
[3] Loesche et. al. 2014, APJ 792, pp. 73

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