PHOTOPHORETIC STRENGTH ON CHONDRULES. 1. MODELING

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ABSTRACT

Photophoresis is a physical process that transports particles in optically thin parts of protoplanetary disks, especially at the inner edge and at the optical surface. To model the transport and resulting effects in detail, it is necessary to quantify the strength of photophoresis for different particle classes as a fundamental input. Here, we explore photophoresis for a set of chondrules. The composition and surface morphology of these chondrules were measured by X-ray tomography. Based on the three-dimensional models, heat transfer through illuminated chondrules was calculated. The resulting surface temperature map was then used to calculate the photophoretic strength. We found that irregularities in particle shape and variations in composition induce variations in the photophoretic force. These depend on the orientation of a particle with respect to the light source. The variation of the absolute value of the photophoretic force on average over all chondrules is 4.17%. The deviation between the direction of the photophoretic force and illumination is $3.0 \pm 1.5$. The average photophoretic force can be well approximated and calculated analytically assuming a homogeneous sphere with a volume equivalent mean radius and an effective thermal conductivity. We found an analytic expression for the effective thermal conductivity. The expression depends on the two main phases of a chondrule and decreases with the amount of fine-grained devitrified, plagioclase-normative mesostasis up to factor of three. For the chondrule sample studied (Bjurböle chondrite), we found a dependence of the photophoretic force on chondrule size.

Key words: methods: numerical – planetary nebulae: general – planets and satellites: formation – protoplanetary disks

Online-only material: color figures

1. INTRODUCTION

It is widely accepted that disks consisting of solids and gas give birth to planetary systems. However, many aspects of the formation process are still poorly understood. Some constraints come from the analysis of matter from the solar system in the form of primitive chondritic meteorites. In chondrites, components with different histories can be found. Calcium–aluminum-rich inclusions (CAIs), condensed directly from the gas phase, are among the oldest materials radiometrically dated due to their high condensation temperature (Amelin et al. 2002; Wadhwa et al. 2007). Chondrules, major components of chondrites, likely formed by the melting of dust agglomerates. Although it is still not clear which processes lead to chondrule formation, it is well known that chondrules formed within a few million years after the first CAIs (Scott 2007). Chondrules and CAIs are often found together in the same chondrite, embedded in a fine-grained matrix consisting of silicate dust.

The non-homogeneous composition of many meteorites is evidence for radial mixing of solid particles in the early solar system. Particles forming at different times and in different places within the solar nebula can be found in the same meteorite. However, the complementarity of matrix and chondrules, the fact that volatile elements depleted in chondrules are enriched in the matrix, restricts the relative transport of chondrules and dust (Keller & Palme 1999; Hezel & Palme 2010). Evidence for more local transport can be inferred from the existence of meteorites with chondrules of different sizes, which implies the operation of a size-sorting mechanism (Kuebler et al. 1999; Scott et al. 1996; Hughes 1978; Cuzzi et al. 1996; Liffman 2005). One example could be the chondrules of the carbonaceous, geochemically related CR–CH–CB-chondrite clan, whose chondrule sizes vary considerably from $<100 \, \mu m$ (CH-chondrites) to about cm-sized in CB-chondrites (Weisberg et al. 1995, 2010; Bischoff et al. 1993a, 1993b; Krot et al. 2005).

Cometary studies give further evidence for radial transport in the early solar system. Comets largely consist of ice and, therefore, must have formed in the outer parts of the solar system. In several comets, refractory minerals have been found by remote sensing (Sitko et al. 2004; Wooden et al. 2004). Samples of comet Wild 2, which were collected by the Stardust spacecraft, also contain high-temperature materials, which likely formed close to the Sun (Zolensky et al. 2006; Brownlee et al. 2006).

Various scenarios have been proposed to explain this radial redistribution and transport. The transport of solid particles is strongly coupled to the gas dynamics in protoplanetary disks. Turbulence is a driving motor for gas flow (Bockelée-Morvan et al. 2002; Cuzzi et al. 2003). As small particles couple well to gas movements, this leads to a random radial redistribution of solid particles. Some models, taking into account the vertical disk structure, describe a radial outflow of particles due to pressure gradients within protoplanetary disks (Ciesla 2007; Keller & Gail 2004). Other models use additional processes to explain the radial outbound movement of solid particles. For example, the X-wind model is based on ionized gas, which couples to the magnetic field of the central star and the inner disk. Particles in the direct environment of the star can be driven up and outward (Shu et al. 1996, 1997). All transport models strongly depend on the assumed underlying disk model parameters.
PHOTOPHORETIC BASICS

2. PHOTOPHORETIC BASICS

The physics behind photophoresis has two regimes. At low ambient pressure, it can be described by the interaction of particle surfaces with individual gas molecules as mentioned previously (free molecular flow regime). At high pressure, photophoresis is balancing the thermal creep of gas in a thin layer along the surface of the particle. While the strength depends on the gas pressure, the effect occurs for any particle that is not in thermal equilibrium with its surroundings. This is the case for any illuminated particle with warmer and cooler sides.

2.0.1. Photophoresis at Low Pressure

In a minimum-mass solar nebula, the mean free path of gas molecules at 1 AU is 1 cm (Hayashi et al. 1985). Chondrules are much smaller than the mean free path, especially farther out in the asteroid belt region. Therefore, we only consider the case of free molecular flow here. The calculation of the photophoretic force then is reduced to calculating the momentum balance of gas molecules impinging and leaving the particle surface. There are two types of collisions of gas molecules with a surface: diffuse and specular reflections. Specular reflections on average do not alter the particle’s momentum. Diffuse reflection refers to the case where the gas molecule is adsorbed onto the surface for a short time and is then ejected in an arbitrary direction. This can change the momentum of a particle since the ejected molecule carries a momentum related to the local surface temperature. The fraction of diffusely reflected molecules, denoted here as $\alpha$, is commonly called the thermal accommodation coefficient. The fraction $\alpha$ is a property of the specific gas species and particle surface and is often considered to be 1.

The surface temperature of an illuminated and absorbing particle is not homogeneous along the surface. Gas molecules leave faster from hot surface parts than from colder parts. The net momentum transfer is given as a surface integral over the particle of the local momentum induced by interactions at the local temperature (Rohatschek & Zulehner 1985; Rohatschek 1995; Hidy & Brock 1970):

$$ F = -\frac{1}{2} \int_0^{S_{\text{par}}} \rho \left( 1 + \sqrt{1 + \alpha \left( \frac{T}{T_{\text{gas}}} - 1 \right)} \right) d\sigma. $$ (1)

Here, $T$ is the particle’s local surface temperature, and $T_{\text{gas}}$ and $\rho$ are the gas temperature and pressure far away from the particle, respectively. $S_{\text{par}}$ is the particle’s surface. Our photophoretic force calculations are based on Equation (1), where we calculate the temperature distribution at the particle surface for a given light flux $I$ as detailed below. We further assume that the accommodation coefficient is constant over the particle surface. Photophoresis is then caused by different surface temperatures, which is sometimes called $\Delta T$ photophoresis (Cheremisin et al. 2005). The case of accommodation coefficients that vary over a particle’s surface is discussed in the literature as $\Delta T$ photophoresis (Cheremisin et al. 2005; Rohatschek 1956a, 1956b). In extreme cases, i.e., a dichotomy over a particle with two different values of $\alpha$, this can cause a significant photophoretic force. This is also the case even for highly conducting particles if the particle temperature is different from
the gas temperature. However, we assume here that the large number of different mineral grains at a chondrule’s surface provide enough averaging that ∆τ photophoresis is unimportant, and we leave detailed studies on ∆τ effects for the future.

Equation (1) is of little practical use for general applications. For this reason, simplifications have been worked out for specific particle types in the past.

2.1. Photophoretic Forces of Spherical Particles

Approximations for photophoresis on well-conducting, spherical particles are given in the literature (Rohatschek & Zulehner 1985; Beresnev et al. 1993). These are sufficient for general estimates on particle transport. However, Loesche & Wurm (2012) found that the deviations from the real photophoretic force can be up to a factor of three (depending on the setting), which is not sufficient for accurate estimates, e.g., on the sorting capability. Therefore, we developed a more accurate and complex but still analytic equation to describe photophoretic forces for homogeneous spherical particles at low pressure. It is (Loesche & Wurm 2012)

\[
F = F \left( r, k, \alpha, I, T_{\text{gas}}^{\text{kin}}, T_{\text{gas}}^{\text{opt}} \right)
= \left( 0.7231 - 0.1741 e^{-2.1804 \left( W/(m^2K) \right) + 0.4316 e^{-0.9251 \alpha} } \right)
\cdot \alpha \pi \frac{p}{6} \frac{k}{T_{\text{gas}}^{\text{kin}}} \frac{1}{r^2} \left[ \frac{k}{r} + 4 \sigma \left( \frac{I}{4 \sigma} \right)^{\frac{1}{4}} \right]^{-1}.
\]

where \( k \) is the thermal conductivity of the particle, \( \sigma \) is the Stefan-Boltzmann constant, \( r \) is the particle radius, \( I \) is light flux density, and \( T_{\text{gas}}^{\text{opt}} \) and \( T_{\text{gas}}^{\text{kin}} \) are the temperatures of the radiation field and the thermal energy of the gas molecules, respectively. The latter two can be different in optical thin environments.

This equation can also be used for onion shell-like particles if the effective thermal conductivity is attributed to the particle (Loesche & Wurm 2012). We will name this \( x \) here to distinguish it from \( k \)-values of the constituents.

2.2. Nonhomogeneous, Nonspherical Particles

For homogeneous spheres or onion-shell particles, the photophoretic force is directed along the line of illumination due to symmetry, and the most important particle property to consider is the thermal conductivity \( x \). For nonhomogeneous and nonspherical particles, the force does not necessarily move a particle in the direction of the light, and the absolute force can also vary with the orientation of a particle in a given illumination field. The goal here is to evaluate these variations of the photophoretic force (magnitude and direction) for a chondrule. The basic means to do so is by calculating the force with a given detailed composition using Equation (1). It has to be noted that it is not clear, a priori, that variations in photophoretic forces for different orientations of a particle are small. Therefore, even though measurements for average thermal conductivities exist for meteorites (Opeil et al. 2010, 2012), these averages of thermal conductivities cannot be used for photophoretic force calculations of chondrules as quantifying the deviations was one major goal of this work.

It is clear that Equation (1) is not useful for the description of the average behavior of particles for further use in photophoretic transport models. Eventually, some effective thermal conductivity might be representative for describing photophoresis on chondrules. If so, and if a characteristic size for the (nonspherical) chondrule can be given, Equation (2) can also be used to calculate the average photophoretic force for nonspherical particles.

Variations in photophoretic force can be caused by two aspects, the inhomogeneity and the nonsphericity. To estimate either one, we reduce the real chondrules. To compare the force on a real chondrule to photophoresis on a spherical but inhomogeneous particle, we calculated a spherical approximation of a chondrule by inscribing the largest spherical particle that fits into the chondrule but keep the original inhomogeneity (Figure 1). To consider the pure effect of the nonsphericity of the chondrule, we also consider particles of chondrule shape that are chemically homogeneous, i.e., attributing them to a single \( k \). This allows us to separate effects of nonsphericity and inhomogeneities (if different) on the direction of photophoretic forces and the variations of the absolute force. In summary, the steps within this paper are to

1. numerically evaluate the photophoretic force on chondrules of a measured shape and composition;
2. numerically evaluate the photophoretic force on spherical particles of chondrule composition;
3. numerically evaluate the photophoretic force on chondrule-shaped but homogeneous particles;
4. quantify deviations in the direction of the photophoretic force with respect to the illumination for the real chondrules, the inhomogeneous sphere approximations, and the homogeneous models of chondrule shape;
5. find a suitable average radius of a chondrule with respect to the photophoretic force; and
6. find a suitable effective thermal conductivity depending on chondrule composition.

3. FROM THREE-DIMENSIONAL TOMOGRAPHY TO SURFACE TEMPERATURE MAPS

3.1. Tomography

For this study, we used a sample of 19 chondrules from the Bjurböle chondrite (L/LL4-chondrite type). The heat transfer calculations require the chondrule shape and the composition...
troilite FeS obtained at a resolution of 5.26 μm/voxel. High mean atomic weight materials are bright.

Figure 2. Typical X-ray tomogram (contrast enhanced) of a Bjurböle chondrule obtained at a resolution of 5.26 μm/voxel. High mean atomic weight materials are bright.

(thermal conductivity according to mineralogy) of the chondrules. To obtain accurate digital representations of their surfaces and interior, we used synchrotron X-ray microtomography (μCT) followed by digital data extraction (e.g., Friedrich et al. 2008; Sasso et al. 2009). Chondrules were imaged at a resolution of 5.26 μm/voxel with 30 keV monochromatic X-rays at the 13-BMD synchrotron beamline located at the Advanced Photon Source (APS) of Argonne National Laboratory with the experimental setup presented in Ebel & Rivers (2007).

To facilitate throughput, we collectively analyzed the chondrules in a specially constructed poly(methyl methacrylate) honeycomb-like receptacle. Each chondrule was placed within an individual cell for analysis; this facilitated post-examination identification and the retrieval of individual chondrules. Therefore, all chondrules were analyzed under identical experimental conditions and adequate space was present between them to facilitate later digital separation. After isolating the volume surrounding each chondrule, we used BLOB3D (Ketcham 2005) to obtain abundances of mineralogical components, porosity, bulk volume, and density. BLOB3D allows for the digital separation, segmentation, and quantification of materials present in digital volumetric data sets such as those produced by our apparatus. A typical tomographic slice is shown in Figure 2.

3.2. From Tomography to Three-dimensional Model

After tomographic analysis, a series of slices existed for a given chondrule. All boundary points separating the background from the chondrule material were extracted from these slices. The resulting boundary point cloud was then converted into a geometric object containing parameterized surfaces (called NURBS). For a chondrule’s interior, the grayscale values from tomography were mapped to certain minerals. Each chondrule is composed of Fe, Ni-metal, FeS, olivines and pyroxenes, a fine-grained devitrified, plagioclase-normative mesostasis, and voids (Figure 3). Thermal conductivities resembling these materials were used at each point (Table 1). A sample tomogram used for k-assignment is shown in Figure 2. In general, the thermal conductivities of the minerals are functions of the temperature. For T > 200 K, Opeil et al. (2012) find a 1/T dependence for meteoritic material. Furthermore, the thermal conductivities are also dependent on the porosity within the chondrule. In our chondrule set, we do see microcracks in the tomography on the single voxel level. However, cracks can occasionally span wide nets within chondrules. We assigned a low thermal conductivity of 0.01 W m⁻¹ K⁻¹ to any empty space to account for radiative heat transfer within. We also consider the mesostasis to be porous and therefore attribute a low thermal conductivity to the mesostasis independent of the actual mineral conductivity. This is an estimate. According to the temperature dependence of the thermal conductivity, the absolute values of the photophoretic force will change with temperature as well. The scaling to account for temperatures at different locations in the solar nebula would be subject to further research and is beyond this study. Again, possible unresolved microcracks lower the thermal conductivity, which is another scaling factor. However, we consider this approach for attributing a single thermal conductivity as suitable for the evaluation of relative variations of the photophoretic force with orientation due to variations in composition and shape.

In the μCT images, the fine-grained devitrified mesostasis areas appear in darker grayscales than the (in most cases) considerably coarser-grained olivines and pyroxenes (Figure 2). However, these “mesostasis areas” still contain variable abundances of olivine and pyroxenes, also visible in Figure 2, that cannot be appropriately resolved based on instrumental limitations.

3.3. Calculating Surface Temperature Maps from Three-dimensional Models

Chondrule shapes and compositions extracted from tomography volumes were imported into a finite element method software (COMSOL®). We then numerically solved heat transfer through the chondrule by solving the stationary heat transfer equation

$$\nabla \cdot k \nabla T = 0.$$  \hspace{1cm} (3)

As a boundary condition, we included cooling through thermal emission in all directions and heating through absorption of illumination from a given direction. We assumed an emissivity for thermal radiation of 1. For a plane wave light source (light
Figure 4. Average photophoretic force for different numerical resolutions and chondrules, normalized to the value achieved with the highest resolution possible. Values converge at the higher mesh resolutions. (A color version of this figure is available in the online journal.)

Table 1

| Material                                         | Gray Shade | Estimated Gray Value | $k$ (W m$^{-1}$ K$^{-1}$) | $c_p$ (J kg$^{-1}$ K$^{-1}$) | $\rho$ (g cm$^{-3}$) |
|--------------------------------------------------|------------|----------------------|----------------------------|----------------------------|---------------------|
| Fe, Ni-metal                                     | White      | $>0.7$               | 80.4                       | 447                        | 7.96                |
| FeS (IronII)-sulfide, troilite                   | Light gray | 0.35-0.7             | 4 (mean)                   | 588.5 (mean)               | 4.61 (normal temp.) |
| Olivine and pyroxene                             | Gray       | 0.17-0.35            | 4.6 (mean)                 | 620 (mean)                 | 3.45                |
| Fine-grained devitrified, plagioclase-normative mesostasis | Dark gray | 0.1-0.17             | 0.1 (estimate)             | 530 (estimate)             | 3.0                 |
| Void                                             | Black      | $<0.1$               | 0.01 (estimate)            | 1                          | 0.1                 |

Notes. Typical Bjurböle olivine and pyroxene have a density of about 3.5 and 3.4 g cm$^{-3}$ respectively. Considering a plagioclase-normative mesostasis having about 50% plagioclase (An10-15) and 50% mafic silicates, a density of about 3.0 g cm$^{-3}$ can be estimated. However, in this paper only a stationary problem is solved, so $c_p$ and $\rho$ have not been used yet.

References. (1) Halliday et al. 2009; (2) Tipler et al. 2009a; (3) Tipler et al. 2009b; (4) Robie & Hemingway 1984; (5) Loesche & Wurm 2012. COMSOL uses tetrahedral meshes consisting of finite elements (edges) of certain lengths. In the free molecular flow regime, the absolute force depends linearly on the absolute ambient pressure. Where absolute numbers are necessary, below we considered the ratio of photophoretic force over pressure.

3.3.2. Parameter Space

Light flux and ambient temperature were chosen to match experimental values. The light flux corresponds to a radial distance of 0.26 AU for a 1 $L_\odot$ star when opacity is not considered. Since the asteroid belt is at about 3 AU, a light flux of 152 W m$^{-2}$ would be expected. The ambient temperature was chosen to match experimental conditions for comparison (room temperature). In protoplanetary disks, temperatures vary from tens of kelvin to sublimation temperatures. It might be worth noting that the typical difference in temperature over a 1 mm diameter particle with thermal conductivity of 0.5 W (m K$^{-1}$) at the given light flux is 37 K between the warm and cold side. However, while we use specific values here, we give only relative outcomes, and the absolute values are not important in the context of this paper.

3.3.1. Numericals

This method was already used and extensively tested in Loesche & Wurm (2012). COMSOL uses tetrahedral meshes consisting of finite elements (edges) of certain lengths. In the highest resolution that can be calculated, the mean size of a mesh cell is 23 $\mu$m. In relation to a tomography resolution of 5.26 $\mu$m, this is comparable, but refinements of the mesh can slightly alter the fine structure simulated.

Numerically, calculations show a very strong convergence in terms of both orientation of the photophoretic force and absolute force value with decreasing mesh size (Figure 4). Variations between the two highest resolution meshes are on the order of 2% of the average absolute force (discussed below), which we attribute to the slight changes in resolving the tomographic details.

4. PHOTOPHORETIC FORCES

4.1. Full Chondrules

The resulting photophoretic forces were calculated from a surface’s temperature field by Equation (1). In the free molecular flow regime, the absolute force depends linearly on the absolute ambient pressure. Where absolute numbers are necessary, below we considered the ratio of photophoretic force over pressure.

We calculate the photophoretic force for real chondrules with their detailed shape and composition for $N = 100$ different orientations with respect to the light source. The different orientations of the light source are distributed evenly surrounding the chondrule by placing them along a spiral (Rakhmanov et al. 1994)

$$\phi(N,t) = 2[N^{0.485}] \arccos \left( \frac{1 + N - 2t}{1 - N} \right),$$

$$\theta(N,t) = \arccos \left( \frac{1 + N - 2t}{1 - N} \right),$$

where $\phi$ and $\theta$ denote the spherical coordinates of incident light and the integer parameter $t$ addresses each point. The spiral is seen in Figure 5.
4.1.1. Angular Deviation to Incident Light Direction

The angular deviation, $\xi$, of the photophoretic force from the direction of incident light is shown in Figure 6. Here, error bars represent standard deviations ($1\sigma$) over the 100 orientations and line markers indicate maximum and minimum values.

The total average over all chondrules is $\xi = 3.0 \pm 1.5$ (standard deviation). The force deviates only modestly with illumination direction. Nevertheless, it implies a small sideward motion of illuminated chondrules. Such a sideward motion is indeed visible in drop tower experiments. Details are discussed in Paper II.

4.1.2. Variation of Absolute Forces

With inhomogeneity and nonsphericity, the absolute force varies with orientation of the light source. The relative deviations of the absolute force to the average photophoretic force are shown in Figure 7. Typical deviations are a few percent. The average is $\pm 4.17\%$.

4.2. Spherical Chondrules

Variations of photophoretic force in direction and strength might be attributed to inhomogeneities of mineral distribution throughout the particle or the shape of the chondrules or a combination of these factors. This can be studied by comparing the results to calculations with spherical particles. To estimate the effect of chondrule composition, we reduce real chondrules to spherical models by inserting spheres of maximum size (centered at the center of shape) that still completely fit inside. Otherwise, we hold the composition within the volume enclosed by the sphere as in the original chondrule and calculate the photophoretic force as described above. In some cases, voids at the surface of these inscribed spheres existed. To simulate a spherical particle, we assigned olivine and pyroxenes to the voids.

4.2.1. Angular Deviation to Incident Light Direction

The total average of all angles for inhomogeneous but spherical particles is $1.81 \pm 1.59$. Figure 8 shows a similar impact of inhomogeneity and asphericity on the scattering angle, $\xi$. 
4.2.2. Variation of Absolute Forces

The average variation of the force to the average force ratio is 3.25%. A comparison to the real chondrules is given in Figure 9.

The spherical particles with chondrule composition show deviations of the photophoretic force in direction and absolute value on the same order as the deviations for the real chondrule calculations. Therefore, the nonhomogeneous composition is taken as a significant parameter influencing the photophoretic force.

4.3. Homogeneous Particle of Chondrule Shape

To get the full picture, the dependence of shape was studied as well. We considered particles of chondrule shape but attributed certain constant thermal conductivities to their interior. Again, the deviation of the photophoretic force from the direction of incident light, as well as the variation in absolute value, was calculated. We only briefly discuss one chondrule-like particle here.

4.3.1. Angular Deviation to Incident Light Direction

Figure 10 shows the average angle $\xi$ between $e_I$ and $F$ for the chondrule with different thermal conductivities. The average of all angles is $2.54 \pm 1^\circ$.

4.3.2. Variation of Absolute Forces

Average photophoretic forces ($F/p$) and their deviations are shown in Figure 11. For spherical particles, Equation (2) can be used to calculate photophoretic forces. Here, we can use this equation to test whether a given size can be used to describe a chondrule as a sphere. We find that the radius of a volume equivalent sphere describes a chondrule-shaped particle very well. Such a function (Equation (2)) has been fitted for a radius and is overplotted in Figure 11 for one example.

As with the previous calculations for real chondrules and spherical particles with chondrule composition, the photophoretic force for homogeneous chondrule shape particles has a certain variation of a few percent slightly increasing with increasing $k$ (see Figure 12).

To test the hypothesis that the equivalent volume sphere radius $r_s$ enters in the calculations, we considered an ellipsoid as another particle shape. The mean force for all different thermal conductivities, even in this case of a very aspherical particle of an ellipsoid with half-axes $(1, 2, 3)$ mm, could also be well approximated by a sphere with equivalent volume radius $r_s = 1.82$ mm (see Figure 13).
5. PHOTOPHORETIC PROPERTIES OF CHONDRULES

The calculations using real chondrule parameters, spherical particles of chondrule composition, and homogeneous particles of chondrule shape show that variations in direction and strength within a few percent occur. Deviations from perfect spheres, the shape as well as the non-uniform composition, induce variations of the same order.

Overall, the variations are rather small, and for general transport models, it might be sufficient to use average values. We determine these averages from the composition and as calculated analytically from Equation (2) as follows.

Homogeneous chondrule-like or ellipsoidal particles (see Section 4.3) could be well described by a sphere with the radius of an equivalent volume sphere. For actual chondrules, the effective thermal conductivity \( \kappa \) is the value at which the mean photophoretic force \( F \) of the calculated sphere fits the calculated force of the real chondrule (Equation (2)). Figure 14 shows the effective thermal conductivity over volume fraction of mesostasis and olivine and pyroxenes. These are the two main components and differ largely in their individual thermal conductivities. There is a strong correlation.

Figure 15 has the olivine and pyroxene fit reverted. Both can be described by one average third-order polynomial as

\[
\kappa(r_s) = (2360r_s + 1.49) \frac{W}{\text{m K}}
\]

where \( x \) is the mesostasis share in the corresponding two-phase system. Taken together, we find that in spite of detailed compositional differences and shapes, we can well describe the chondrule by an effective thermal conductivity only based on the ratio between the two primary phases (Equation (7)). Hence, other chondrules of the same type (L/LL4-chondrite type) need only to undergo a determination of the mesostasis and olivines and pyroxenes share as well as the volume, so that \( \kappa \) and eventually \( F \) can be calculated.

The results of the calculations are summarized in Table 2.

While this can now be applied more easily in general transport models, one immediate application to see here is the correlation between the two parameters quantifying the photophoretic force—thermal conductivity and size. This is shown in Figure 16.

There is a slight trend that the thermal conductivity varies with size, which allows a size sorting according to photophoresis at low pressures (Loesche & Wurm 2012; Wurm & Krauss...
Table 2
Chondrule Properties

| Sample | Total Volume (mm³) | Porosity | Fine-grained Devitrified Olivines and Pyroxenes | FeS (Troilite) | Fe, Ni-metal | Radii (mm) | Eff. Thermal Conductivity (W/m·K) |
|--------|--------------------|----------|-----------------------------------------------|----------------|-------------|------------|----------------------------------|
|         |                    |          |                                               |                |             | r_max     | r_s     | r_min | Mean | STD Interval |
| 1       | 5.065              | 1.4      | 21.4                                          | 74.6           | 2.0         | 1.36       | 1.065   | 0.82  | 2.60 | 2.54–2.67    |
| 2       | 0.020              | 2.3      | 38.0                                          | 59.6           | 0.0         | 0.24       | 0.167   | 0.09  | 2.28 | 2.06–2.57    |
| 3       | 0.096              | 3.0      | 34.5                                          | 62.5           | 0.0         | 0.36       | 0.284   | 0.20  | 1.84 | 1.79–1.90    |
| 4       | 0.398              | 2.1      | 31.0                                          | 65.6           | 1.2         | 0.56       | 0.456   | 0.34  | 2.06 | 2.00–2.13    |
| 5       | 0.369              | 0.6      | 27.4                                          | 70.7           | 1.3         | 0.53       | 0.445   | 0.38  | 3.11 | 3.04–3.19    |
| 6       | 0.227              | 0.1      | 22.5                                          | 77.3           | 0.0         | 0.43       | 0.379   | 0.28  | 3.51 | 3.47–3.54    |
| 7       | 0.189              | 4.3      | 39.4                                          | 55.3           | 1.0         | 0.41       | 0.356   | 0.25  | 2.19 | 2.13–2.26    |
| 8       | 0.122              | 7.8      | 54.2                                          | 37.7           | 0.3         | 0.39       | 0.308   | 0.17  | 1.25 | 1.20–1.30    |
| 9       | 0.186              | 0.2      | 64.8                                          | 34.9           | 0.0         | 0.51       | 0.354   | 0.24  | 1.38 | 1.32–1.46    |
| 10      | 0.226              | 3.3      | 31.8                                          | 63.2           | 1.5         | 0.53       | 0.378   | 0.27  | 2.50 | 2.44–2.56    |
| 11      | 0.186              | 1.9      | 19.7                                          | 78.3           | 0.1         | 0.41       | 0.354   | 0.27  | 3.46 | 3.44–3.49    |
| 12      | 0.766              | 4.8      | 44.9                                          | 48.1           | 1.9         | 0.73       | 0.568   | 0.32  | 1.96 | 1.86–2.08    |
| 13      | 0.535              | 1.1      | 22.3                                          | 70.0           | 4.8         | 0.62       | 0.504   | 0.39  | 3.58 | 3.46–3.70    |
| 14      | 0.063              | 4.3      | 30.6                                          | 65.0           | 0.0         | 0.33       | 0.246   | 0.18  | 2.42 | 2.30–2.54    |
| 15      | 0.036              | 4.7      | 57.2                                          | 35.9           | 2.0         | 0.29       | 0.205   | 0.14  | 1.18 | 1.11–1.27    |
| 16      | 0.068              | 2.7      | 43.1                                          | 54.2           | 0.1         | 0.29       | 0.253   | 0.17  | 2.12 | 2.09–2.15    |
| 17      | 0.182              | 2.9      | 40.2                                          | 56.8           | 0.1         | 0.45       | 0.351   | 0.22  | 2.04 | 1.94–2.15    |
| 18      | 0.429              | 2.1      | 29.6                                          | 63.9           | 2.8         | 0.66       | 0.468   | 0.33  | 2.95 | 2.68–3.28    |

2006, but this depends on the disk model and is subject to further research.

6. CONCLUSIONS

We currently consider photophoresis to be one of the major forces acting on particles in optically thin regions of protoplanetary disks. This is especially true at the inner disk edge, where photophoresis is responsible for local transport (Haack & Wurm 2007; Loesche & Wurm 2012; Wurm & Haack 2009). As detailed in the preceding sections, we quantified the photophoretic force on chondrules in this work. We found that the photophoretic force on chondrules can be well approximated by Equation (2) for spherical particles. A radius of 1 AU in a minimum-mass solar nebula (Hayashi et al. 1985).

Independent of the specific surface morphology or mineral distribution within the chondrule, the mean absolute forces vary on average by 4.17%, depending on orientation. Inhomogeneity and shape both have a similar influence.

The direction of the photophoretic force for chondrules is centered on the direction of the incident light with average deviations of 3°0 ± 1°5. Such deviations will induce small sideways forces and motions. We did not yet quantify torques and rotation induced by photophoresis as seen in experiments by van Eymeren & Wurm (2012).

In Paper II, we report experimental measurements of the photophoretic force on the same set of chondrules and compare the results to the calculations given in this paper.

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