Photophoretic forces on chondrules in drop tower experiments

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**Abstract.** Studies of meteoritic and cometary materials give evidence for radial mixing of solid material within the early solar system. Among other transport mechanisms, photophoresis is a proposed mechanism for radial material transport in protoplanetary disks. Within this study, the photophoretic motion of chondrules in microgravity is investigated in drop tower studies. Chondrules form the meteorite Bjurböle were exposed to an intense laser beam. The acceleration due to photophoresis was observed and tracked with two cameras. The experimental results give evidence that photophoresis indeed is an efficient transport mechanism for chondrules and other small particles in the solar nebula. The measured values for the photophoretic force correspond well to the results of earlier studies and show clearly, that the models for particle transport by photophoresis are in agreement with the experimental data.

1. Introduction

In the early solar system the young sun was surrounded by a protoplanetary disk, the Solar Nebula [1]. It consisted of gas and embedded dust particles. This medium initially was optically thick for radiation of the visible wavelength range. With the dust being subject to different processes of accretion, e.g. the formation of planetesimals, protoplanets, terrestrial planets etc., the dust reservoir in the disk diminished and the disk eventually became optically thin. The gas molecules, too, were subject to processes that decreased the gas content of the disk, for example photoevaporation or solar wind [2]. However, in the standard model of giant planet formation, gas is accreted onto a solid nucleus of several earth masses, which implies that the gas still has to be dense while the dust is already further evolved into large aggregates. This implication is equivalent to the conclusion that the protoplanetary disk has a state, where it is at least partly optically thin and yet still rich in gas. Combinations of optically thin inner disks and optically thick outer disks are well observed these days [3]. In these transitional disks with inner holes extending up to several AU there is no doubt that the particles at the inner edge of the outer disk are illuminated by starlight but are embedded in a gaseous environment. The existence of such a disk-state gives way to a particle sorting and concentration process that is based on photophoresis, a light induced force besides radiation pressure, Poynting-Robertson drag and the Yarkovski effect. While the latter are based on momentum transfer by photons, for photophoresis gas molecules in the vicinity of the observed particle act as mediators. The principle of photophoresis is shown in figure 1 for the simple case of a spherical particle:

The particle-side facing towards the radiation source is heated to the higher temperature $T_2$ and a temperature gradient in direction of the incident radiation builds up depending on
Figure 1. Principle of photophoresis: the ideal spherical particle is heated by radiation from the left side resulting in a temperature gradient in direction of the incident light. Gas molecules sticking to the surface leave the particle at different thermal velocities (faster on the warmer side). To conserve momentum the particle has to balance this mismatch and is accelerated away from the light source.

Due to the assumed isotropy of the ambient gas atmosphere and the rotational symmetry of the temperature distribution around the incident direction of the light, only the momentum components along this direction of light account for the change in momentum of the particle. Hence the acceleration of the particle is directed away from the light source or outward in protoplanetary disks. Quantitative descriptions for this process exist for simple cases as, for example, the aforementioned perfect sphere with an absorption coefficient of 100%. The photophoretic force is

\[ F_{ph} = \frac{\pi a^2 I_p J_1}{3k_{th}T_a} + 12\sigma T^3 + \frac{p}{\rho m_g} \left( \frac{18kT}{\pi m_g} \right) \approx \frac{\pi a^3 I_p}{6k_{th}T}. \]  

Here the particle parameters are the radius \( a \) and the thermal conductivity \( k_{th} \) and the properties of the ambient gas are the temperature \( T \), the molecule mass \( m_g \) and the pressure \( p \). \( k \) and \( \sigma \) are the Boltzmann- and Stefan-Boltzmann-constant and \( I \) is the radiative flux (or intensity). \( J_1 \) is the asymmetry parameter, taking into account the light-absorption properties of the particle, \( J_1 = 0.5 \) for perfect absorption at the front side, respectively. At a distance of 1 AU to the star the pressure is \( p = 1 \text{ Pa} \) and the temperature \( T = 280 \text{ K} \) in the minimum mass solar nebula [6]. Assuming a thermal conductivity of \( k_{th} = 0.1 \text{ W/(m K)} \) one finds for the radiation pressure \( F_{rp} \approx F_{ph} \times 10^{-3} \) assuming \( F_{rp} = I/c\pi a^2 \) [7]. As Poynting-Roberston drag and the Yarkovski effect are based on radiation pressure they are still smaller.

In comparison photophoresis turns out to be the dominant force and the other forces can be neglected if the ambient conditions (namely an optically thin medium with still high enough gas density) allow for photophoresis to take effect.

The aim of this paper is to show our recent experimental developments to determine the
absolute strength of photophoresis on certain particle classes. Based on these, eventually, one goal is to study the sorting and concentration efficiency of photophoresis concerning a special type of particles: chondrules. Chondrules are sub-mm- to mm-sized, almost spherical particles, consisting mainly of Mg-Fe silicates. They occur at concentrations of up to 80% in specimens of a class of stony meteorites called chondrites, embedded in a fine-grained matrix [8]. There is a consensus that chondrules are formed from precursor materials by flash heating and adjacent fast cooling in the early solar nebula, whereas the source of heat for this process is still subject to discussion. Studies have shown that the overall formation of the chondrule reservoir in the protoplanetary disk takes about two to three million years, while individual chondrites can contain chondrules with up to one million years of age difference [9]. An interesting fact is that chondrules partially seem to be sorted by size [10]. This shows the necessity of a locally effective transport and concentration mechanism.

To characterize the motion of particles in the protoplanetary disk under the influence of photophoresis, let, without loss of generality, the gas density profile be

$$\rho = 1.4 \times 10^{-6} \left( \frac{R}{\text{1AU}} \right)^{-11/4} \text{kg m}^{-3}$$  \hfill (2)

according to the minimum mass Solar Nebula model of [6] (with R being the radial distance to the star). The radial density gradient causes a pressure gradient which imposes a force upon the gas molecules. This results in an altered (in this case slowed down) rotational speed than predicted by Kepler’s laws, to establish a stable orbit. The subsequent gas drag decelerates the solid particles to the velocity of the gas. However, as they are too dense to be supported by the pressure gradient, according to [11] they are subject to a residual gravity

$$F_D = \frac{n R_{\text{Gas}} T m_P}{\mu R},$$  \hfill (3)

with $n = 11/4$ the exponent of the density profiles power law, $R_{\text{Gas}}$ the gas constant, $\mu$ the molar mass and $m_P$ the mass of the particle. Opposing this inward drift is the outward directed photophoretic force. The ratio of the photophoretic force and the residual gravity is given as [7,12]

$$\frac{F_{ph}}{F_D} = \frac{\mu I p R}{k_{th} \rho_P S n R_{\text{Gas}} T^2}. $$  \hfill (4)

If this value is larger than 1, particles move outwards. This is the case for particles close to the star. If the value is smaller than 1 a particle moves inwards which is the case for particles far away from the star. For $F_{ph}/F_D = 1$ equilibrium exists where particles are concentrating and no further radial transport takes place. If the strength of the photophoretic force varies for different kinds of particles, so does the position of the equilibrium. This way a simple sorting is possible. With $k_{th}$ and $\rho_P$, the thermal conductivity and the mass density sorting can depend on particle properties. Also, assuming that the chondrules might already be covered in a dust mantle of the fine-grained matrix-material during the transport, the review by [13] shows that the thermal conductivity of a mixture is dominated by the size of the larger constituent. So essentially the sorting by photophoresis is a possible mechanism to explain the meteoritical evidence.

Unfortunately, little data exists on the photophoretic forces on chondrules as the details depend on a large number of parameters not easily accessible. Direct measurement for free particles allow to quantify the strength of photophoresis but they need microgravity. In an earlier drop tower campaign we tested the feasibility of determining the photophoretic force [14]. Indeed we could show that rough estimates were correct and that the photophoretic force on dust mantled chondrules is stronger than on bare chondrules and that pure dust aggregates experience an even stronger force.
2. Microgravity experiments

To quantify the effect of photophoresis on chondrules, a set of 16 microgravity-experiments was carried out at the ZARM drop tower in Bremen, each providing - in catapult mode - up to 9.3 seconds of weightlessness with a residual acceleration of $10^{-6}g$ or less. This is necessary, because at typical and feasible experimental parameters, Earth gravity is about three orders of magnitude stronger than the expected photophoretic acceleration.

In figures 2 and 3 a sketch of the experimental setup is shown, displaying, with the exception of the enclosing vacuum chamber, the basic components: the housing for the chondrules, the laser light source and the video observation. The housing confines the chondrules movement to an observable space and facilitates their recovery after the experiment. It has four glass windows, two for video observation and one, at the top, as inlet for the laser beam. The fourth window is placed at the bottom of the housing to prevent heating of the housing by laser radiation. As the laser light is then only absorbed by the particles, no thermophoretic forces occur. Inside there are two retractable feeders, the lower one with nine cavities for the chondrules, to keep them in position at the center of the housing until microgravity is established in the drop capsule. They are released automatically by command of the gravity sensor, that is part of the capsule electronics. The transition from normal gravity to microgravity leads to an initial velocity of the particles, which is damped by collisions with the cavity walls. However, the movement of the feeders can itself induce particle rotation and linear motion. The feeders are retracted within 4 ms, which leads to a variety of initial movement of the chondrules in the range form 0 cm/s to about 1 cm/s. A red laser (1W, 655 nm ±10 nm) is used as light source, but, deviating from the sketch, is placed outside the vacuum chamber. Furthermore the laser beam is deflected four times to maximize the optical path and the profile is shaped by two cylindrical lenses to broaden and homogenize the laser profile. Video observation is realized with two synchronized high-speed cameras aligned perpendicular to each other, allowing for the motion of the chondrules to be tracked in all three spatial directions.

To characterize the intensity profile of the laser beam, the light output was measured with a bolometer for surface elements of $4 \text{mm}^2$ at the position of the experiment chamber’s inlet window. This measurement showed a central peak with intensities of up to $27000 \text{W/m}^2$.

For the experiment, nine selected chondrules are loaded into the cavities of the lower feeder and the feeders are clamped. In some experiments transparent 1 mm glass spheres are added to rule out the existence of possible disturbing effects (charging, ...). The pressure in the experiment chamber is set to a predefined value. Experiments were carried out at pressures between 0.01
mbar and 0.1 mbar. In this pressure range the coupling time of the chondrules are large enough to prevent any influence of gas movement, which might be induced by the retracting feeders. After retrieval of the experiment the chondrules are recovered.

The chondrules used in the experiments originate from the meteorite "Bjurböle", a chondrite of the L/LL4-class. After separation they were processed in a grinding mill to remove all remains of matrix material on the surface and then photographed and weighed.

3. Results

The acceleration acting on the chondrules when they are exposed to the intense central peak of the Laser profile is shown in figure 4 using the example of one selected trajectory.

To quantify the particle motion the chondrules were allocated to their respective positions in the feeder at the beginning of the recording and then tracked in the image files of both cameras. In figure 5 the trajectory is plotted component-wise (distance from the reference point against time) and the area of acceleration is marked with a box. The trajectories in the non-illuminated parts of the experiment volume clearly show that no other forces act on the particles, as particles move linearly. Electrical charges and magnetic forces can be ruled out, as the particle motion is not influenced by neighbor particles, despite of particle collisions.

To determine the average acceleration in every direction, the constant velocity-components before and after the acceleration area are derived by applying linear regressions to the data set. This leads to the average acceleration

\[ a_{\text{avg}} = \frac{v_2 - v_1}{t_2 - t_1} \]  

With the given particle masses this can be translated to a photophoretic force \( F \), plotted in figure 6. We get values between \( 7.9 \times 10^{-12} \) N and \( 3.7 \times 10^{-8} \) N which is consistent with earlier data by [14]. The systematic deviation of the measured forces from the calculated values of one
Figure 5. Plot of a chondrule’s trajectory (distance to the reference point in $x$-, $y$- and $z$-direction): The box marks the time span shown in figure 4.

Figure 6. Ratio of the measured photophoretic force and the photophoretic force calculated using equation 1 with $k_{th} = 1$ W/mK, $J = 0.5$ and $\alpha = 1$

to two orders of magnitude can be attributed to the simplified equation used in the calculation and of course to the non-idealistic particle parameters of the real chondrules (e.g. non-spherical shape, variable thermal conductivity, albedo, ...).

4. Conclusions and Outlook
In [14] a set of photophoretic measurements on chondrules, dust mantled chondrules and dust was tested for the first time and allowed us to verify simple estimates of absolute forces on chondrules as they have been used previously [12]. The idea behind the experiments reported here was to achieve data at a qualitatively much better level by using a longer duration of microgravity by using the catapult (9 s instead of 4.7 s), by using new particle cavities to keep chondrules slow and to use a laser as light source to better quantify the light flux. Indeed the particles could be tracked much better and longer and therefore with better accuracy than in the original experiment. In a following campaign, just carried out, the light source was improved providing an almost homogeneous illumination over the entire chamber. These data are not
Figure 7. High accuracy trajectory of a chondrule in time steps of 0.1 s with the most recent setup.

analyzed yet but we currently estimate the measurement errors to be in the ten % range. This is much less then the spread in data in the earlier experiments by [14] or reported above where individual values even for a single chondrule could vary by a factor of a few. A first example of a particle trajectory is shown in figure 7 which is a perfect parabola.

We now have a setup to measure the photophoretic strength and variations for different particles in detail and we do have data but this has just been started to be analyzed at the time of these proceedings. Specific applications to protoplanetary disks therefore have to await this further data analysis but should allow us to specify the variations in photophoretic strength between chondrules in much more detail. As we also used dark material from the Allende meteorite in the recent campaign (low albedo) this will enable us to draw first conclusions from experiments on the capability of photophoresis to transport and sort particles. Last not least we also observed and resolved the rotation of the particles. From the data it can be specified how rotation changes the photophoretic strength or how it is changed by photophoresis.

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5. References
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