PHOTOPHORESIS AND CHONDRULES: A PERFECT COMBINATION TO FORM ASTEROIDS.
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Introduction: We present a model where the hitherto neglected force of photophoresis dominates the motion of particles in late stage protoplanetary disks. We focus on chondrules here, which would be concentrated and sorted due to particle properties (e.g. size) in the region of the asteroid belt.

Photophoresis: When a solid particle absorbs light it usually heats up more on the side facing the light source. Gas molecules that hit the surface are adsorbed and reemitted. They leave faster on the hotter side than on the colder side. A net momentum transfer away from the light source results which pushes a particle away from the light source. Details are more complicated but this is the principle of the effect known as photophoresis [1]. The two basic requirements for photophoresis are

1. the presence of (not too much) gas and
2. the presence of light.

Protoplanetary Disks: In view of current observations and modeling it is rather likely that these two requirements are met in later stages of protoplanetary disks or in young circumstellar disks of solar-mass type stars since dust and gas evolve on different timescales [2]. Dust will probably be depleted on shorter timescales long before the gas is dispersed. Thus, any remaining particle will “see” the star light and will be subject to photophoresis.

We recently found that photophoresis in such gaseous, optically thin protoplanetary disks could be a major force to move particles up to m-size outwards (Krauss and Wurm, this conference) [3]. A natural consequence of the gas pressure dependence of photophoresis is the formation of rings around a star where solids strongly concentrate. The distance at which this concentration occurs depends on the particle properties with thermal conductivity being one of the major parameters. As far as dust aggregates are concerned they should pile-up at several tens of AU from a star and might explain observed dust rings around young stars or even trigger the formation of Kuiper belts [3]. However, there is a distinct difference between the thermal conductivities of “dusty” bodies made up of (sub-)micron-sized particles and bodies with larger compact constituents. It is obviously a similar distinction which is manifested in primitive meteorites where opposing the small dust are large chondrules.

Chondrules: Chondrules are sub-mm-size mostly spherical particles which are highly concentrated in primitive meteorites known as chondrites [4]. As much as 80% (volume) of a chondrite can be constituted by chondrules. The age difference between different chondrules in the same chondrite can be more than 1 Myr [5]. It is not yet settled how chondrules form and it is not easily explained how such a high concentration of chondrules can be achieved in the same chondrite for particles which formed a million years apart. This is especially true in view of most current models of planetesimal formation where aggregation occurs quickly. Any chondrule would be incorporated into a larger object long before a chondrule 1 Myr younger could get close to it.

A further detail is that chondrules in a given class of chondrites are often sorted (apparently) due to size [6]. If large metal grains are present this sorting also applies to the metal grains. In the same chondrite the metal grains are smaller than the chondrules though.

Chondrule Light Barriers: If chondrules are present in a gaseous, optically thin stage of a protoplanetary disk they will inevitably be subject to photophoretic concentration. They will pile-up at a certain distance which we call light barrier. Using typical parameters light barriers as seen in Fig. 1 are the result [7]. Details will be given at the conference.

![Fig. 1. Photophoretic force over residual gravity in a minimum mass solar nebula. Particle sorting and concentration occurs at a ratio of 1 (light barrier). The position of the light barrier depends on the thermal conductivity, assumed to be 1, 0.5, 0.001 Wm⁻¹K⁻¹ from left to right.](image)

Certainly the model has some free parameters (gas and particle density, thermal conductivities …). A different choice would shift the light barriers considera-
bly. However, it is a rare chance that the assumption of typical values would put the light barrier for chondrules in the region of the current asteroid belt where meteorites are supposed to have their origin.

**Conclusions:** So far we only applied the photophoretic concentration mechanism to chondrules in a static model. However, as outlined in Wurm and Krauss [7], this might already explain many features of chondrule sorting and concentration quite naturally. Chondrule size e.g. enters in the thermal conductivities in a compound body. This might explain a “size” sorting and the difference in size of metal grains and chondrules found in the same chondrite.

The basic assumption of our model is that the solar nebula was optically thin and still contained a significant amount of gas for some time and that chondrules were present then. While supported by observations and theory, there is no unambiguous proof yet for the existence of an optically thin gaseous solar nebula. If the gas vanished before or at the same time as the dust did, we clearly note that the whole idea would be obsolete to start with.

However, in view of the supporting facts, in view of the simplicity of the mechanism, and in view of the inevitability of concentration and sorting if photophoresis is applicable, it is very tempting to assume that photophoresis might be the mechanism to lead to the concentration and sorting of chondrules.

To argue the other way round, if the conditions for photophoresis are given it is mandatory to include it into any model of dynamical evolution of particles in a disk due to its extraordinary strength.

As might be deduced from recent collision experiments chondrules should continuously be extracted from larger bodies throughout the evolution of the early solar system (Paraskov et al., this conference) [8]. Thus, even if chondrules formed in an optically thick disk earlier, extraction and concentration by photophoresis later is a plausible, straightforward process. This might also bring particles together that formed a million years apart.

Somewhat related to chondrules are calcium aluminum rich inclusions (CAIs) which are also found in chondrites. If they form close to the sun, photophoresis might prevent them from spiraling into the sun (Wurm and Krauss, also this conference) [7].

As chondrules as part of chondrites are considered to be the building blocks of undifferentiated asteroids eventually we have to argue that photophoresis has triggered the formation of these asteroids. It is then also straightforward to assume that the dust that is pushed further outwards will trigger the formation of comets or Kuiper belt objects (Krauss and Wurm, this conference) [3].

**Acknowledgement:** This work is funded by the Deutsche Forschungsgemeinschaft.