

**PHOTOPHORESIS AS THE DRIVING FORCE FOR THE FORMATION OF CIRCUMSTELLAR DUST RINGS AND (EXO-)KUIPER BELTS.** O. Krauss and G. Wurm, Institute for Planetology, University of Muenster, Wilhelm-Klemm-Str. 10, 48149 Muenster, Germany. e-mail: okrauss@uni-muenster.de

**Introduction:** As protoplanetary disks turn optically thin they often reveal a ring-shaped structure with a dust-free inner region and one or more circumstellar rings of cold dust at distances ranging from some ten AU to several hundred AU. Several models have been proposed to explain this ringlike structure by radial migration of dust particles in the disk due to a combination of forces, of which the most dominant are stellar gravitation, gas drag, and radiation pressure. However, the effect of photophoresis [1], a radiative force on particles in low pressure gaseous environments, has been neglected so far in this context.

In a very recent paper we have introduced photophoresis into astrophysics as a very efficient mechanism for dust migration in circumstellar disks [2]. For this effect to occur only one assumption has to be made. There must be a phase when protoplanetary disks still contain a considerable amount of gas, while the dust has already been processed into larger bodies, leaving the disk optically thin. This is supported by recent observations [3] and theoretical studies [4] that suggest different lifetimes for the gas and the dust component in protoplanetary disks. The formation of dust rings is then a natural consequence of the gas pressure dependence of the photophoretic effect.

**Photophoresis:** Inhomogeneous heating due to the illumination of a particle from one direction leads to a temperature gradient on its surface. The molecules of the surrounding gas that accommodate on the surface leave the particle with different velocities according to the local surface temperature. Thus, a net momentum is transferred to the particle. In the simplest case, an absorbing particle gets hotter on its illuminated side and is pushed away from the light source by the photophoretic force. If the particle size is smaller than the mean free path of the gas molecules (Knudsen number larger than 1), the photophoretic force is proportional to the gas pressure. A low thermal conductivity of the dust material leads to a large temperature gradient over the surface of the particle and a strong photophoretic force. By calculating several force ratios we have shown that the photophoretic force can exceed gravity or radiation pressure by several orders of magnitude, depending on the gas pressure and the particle properties [2]. Especially the dynamics of large particles up to m-size, for which radiation pressure is negligibly small, are strongly influenced by photophoresis.

**The light barrier:** To study the effect of photophoresis in a circumstellar disk we assume a gas density and temperature distribution of a minimum mass solar nebula given by Hayashi et al. [5]. In principle, any disk model with a radially decreasing gas density will lead to the same effect. In such a system the dust grains are embedded in the rotating gas disk and move on sub-Keplerian orbits, resulting in a residual drag force towards the central star [6]. In the inner region, where the gas pressure is relatively high, the photophoretic force is very strong and pushes the dust particles outwards. But with growing distance to the star the gas pressure decreases, and the photophoretic force gets weaker. The particles will reach a point where all inward and outward radial forces are in equilibrium. We call this the light barrier. For a sun-like star the light barrier for particles of mm-size and larger is at about 30 AU, as can be seen in Fig. 1.

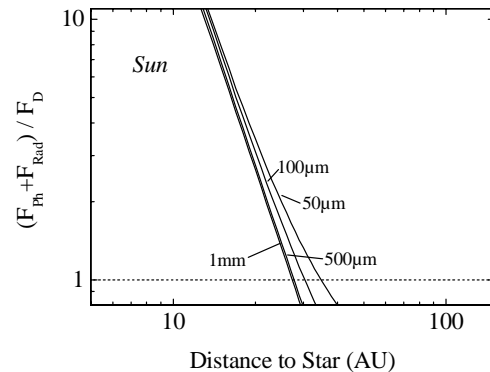


Fig. 1. Calculated ratio of photophoretic force plus radiation pressure to gas drag force for dust particles of several sizes around a sun-like star, assuming a minimum mass solar nebula and a thermal conductivity of the particles of  $0.001 \text{ Wm}^{-1}\text{K}^{-1}$ . The particles are concentrated where the force ratio is 1, the light barrier. Adapted from [2].

**Rings and belts:** As described above the interplay of all forces at work let the particles migrate to a certain distance to the star where all forces are in equilibrium. Since dust particles larger than about  $100 \mu\text{m}$  do not feel the size dependent radiation pressure force, their light barriers lie very close together. The position of the light barriers also depend on the thermal conductivity of the respective particles. Since dust aggregates that have emerged from a collisional growth

process have a very low thermal conductivity they will be driven further out than more compact particles. These fluffy dust aggregates are concentrated at a certain distance to the star by photophoresis. The high concentration of these particles in this region leads to an increased collision rate that produces a large amount of small dust particles that make up the visible dust ring. At the same time this high collisional activity might eventually result in the growth of larger bodies equivalent to Kuiper belt objects (KBOs).

Photophoresis might also be responsible for other classes of material to reach the region of a forming Kuiper belt and be incorporated into KBOs. Recent observations revealed an unexpectedly high silicate crystalline-to-amorphous ratio in Oort cloud comets [7, 8]. Photophoresis might serve as an efficient transport mechanism for crystalline silicate material that is formed in the inner disk where temperatures are high enough to the outer region of the disk.

*HR 4796A.* One prominent object for which a pronounced circumstellar dust ring has been observed is HR 4796A, a main-sequence A-type star with an age of about 8 Myr [9]. This object has a bright dust ring centered at about 70 AU from the star [10 and refs. therein]. In Fig. 2 we show that particles in the 1-mm size regime have their light barrier at about 70 AU, assuming reasonable parameters for the thermal conductivity of the particles and the gas density of the disk. Smaller particles are driven further out. Although the particles that accumulate at the inner edge of the observed ring are larger than the particle size that is retrieved from spectral observations they can serve as a reservoir for smaller grains that are ejected during collisions, as described above.

Observations that suggest that HR 4796A has already lost most of its gas, probably to form gas giant planets [11], are not in contradiction to our model. The system may have already passed the phase of efficient photophoresis, during which material has migrated to the inner edge of the ring. After the gas has disappeared, particles that are large enough will be stable in the ring. Collisions between these bodies will feed the visible dust component of the ring and at the same time lead to the growth of KBOs.

**Conclusion:** With analytical calculations that describe the photophoretic effect and its competing forces we have shown that in a gas-rich and optically thin circumstellar disk photophoresis will have a strong influence on the dust dynamics. The formation of dust rings and Kuiper belts can naturally be explained by the migration of dust particles to the light barrier driven by photophoresis.

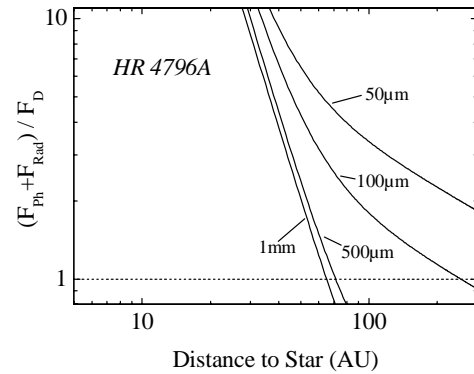


Fig 2. Calculated ratio of the photophoretic force plus radiation pressure to the inward directed drift force for several particle sizes as indicated. Stellar parameters are that of HR 4796A, and the mass of the disk is assumed to be twice that of a minimum mass solar nebula. Large particles are concentrated at about 70 AU, while the smaller grains are blown further out by radiation pressure.

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**References:** [1] Ehrenhaft F. (1918) *Ann. Phys.*, 56, 81-132. [2] Krauss O. and Wurm G. (2005) *ApJ*, 630, 1088-1092. [3] Greaves J. S. (2004) *MNRAS*, 351, L99-L104. [4] Takeuchi T. et al. (2005) *ApJ*, 627, 286-292. [5] Hayashi C. et al. (1985) in *PP II* (ed. Black D. C. et al.), Tucson, 1100-1153. [6] Weidenschilling S. J. (1977), *MNRAS*, 180, 57-70. [7] Wooden D. H. et al. (2004) *ApJ*, 612, L77-L80. [8] Harker D. E. (2004), *ApJ*, 615, 1081-1081. [9] Stauffer J. R. et al. (1995) *ApJ*, 454, 910-916. [10] Wahhaj Z. (2005) *ApJ*, 618, 385-396. [11] Chen C. H. and Kamp I. (2004) *ApJ*, 602, 985-992.