PHOTOPHORESIS AS A SOURCE OF CRYSTALLINE SILICATES IN COMETS. J.-M. Petit[1], O. Mousis[1], Y. Alibert[2] and J. Horner[2], [1]Observatoire de Besançon, CNRS-UMR 6091, 41 bis, avenue de l'Observatoire, BP 1615 Besançon, France (Jean-Marc.Petit@obs-besancon.fr); [2]Physikalisches Institut, Universitaet Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland.

Introduction: Crystalline silicates have been detected in a growing number of comets [1] [2] [3]. Since these bodies are presumed to be formed in the cold outer part of the solar nebula, several processes have been invoked in order to explain the origin of their crystalline silicates. It has been suggested that shock waves in the outer solar nebula could anneal the amorphous silicates to crystallinity *in situ* prior to their incorporation in comets [4]. However, there is no observational evidence for the existence of such processes. In contrast, the formation of crystalline silicates in the inner hot region of the solar nebula and their diffusive transport out to the comet formation zone has been proposed as another possibility [5]. On the other hand, since the diffusive transport of crystalline silicates leads to a homogeneous abundance of grains within the solar nebula, this mechanism is not compatible with the composition gradient observed in comets [3].

In this work, we present calculations relevant to the photophoretic force in the solar nebula [6] [7]. We show that photophoresis can be considered as an alternative transport mechanism that allows crystalline silicates formed in the inner nebula to move outward in the formation regions of cometary reservoirs. Moreover, we find that this mechanism is consistent with the heterogeneity of crystalline silicates abundances observed in comets [3].

Photophoresis in the solar nebula: Photophoresis is the effect based on a radiation-induced temperature gradient on the surface of a particle and the resulting nonuniform interaction with surrounding gas [6] [7]. This induces a photophoretic force which makes the particles move away from the light source. The photophoretic force is pressure dependent and can be stronger than radiation pressure and gravity by orders of magnitude in the solar nebula [6]. It works at its best when the solar nebula becomes optically thin after several millions of years of evolution. As a result, particles ranging in size from 1 μm to 10 m migrate in the late solar nebula under the combined action of photophoresis, radiation pressure and gas drag [6]. Here we examine the migration conditions of crystalline silicate particles initially formed in the inner solar nebula and that were transported by photophoresis in the outer part of the disk. In particular, we focus on the temporal evolution of the transition region where these particles can settle in the outer solar nebula. This transition region results from the equilibrium reached between the photophoresis-dominated outward motion and gas-drag-dominated inward motion.

We have calculated the net motion of dust particles under the influence of photophoresis force F_{ph}, radiation pressure force F_{rad} and gas-drag force F_D in an evolving turbulent model of the solar nebula. The protoplanetary disk is calculated in the framework of the α formalism [8] and the gas surface density Σ evolves as a result of viscous transport and photoevaporation. The thermodynamical properties of the disk as a function of heliocentric distance and surface density, as well as the mean viscosity ν, are calculated by solving the vertical structure equations [9]. The initial mass of the disk is about 0.1 Solar mass.

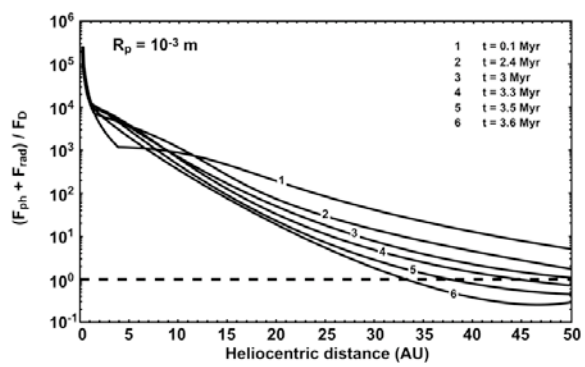

Figure 1: Ratios of the photophoretic force F_{ph} and radiation pressure force F_{rad} to gas drag F_D on particles of the millimeter size as a function of the heliocentric distance at different epochs of the evolving solar nebula. Photophoresis dominates at early epochs in the solar nebula. With time, dust particles start to settle in the outer part of the solar nebula where all forces are in equilibrium. Note that the origin of time in the solar nebula is chosen arbitrarily.

Figure 1 represents the temporal evolution of the equilibrium position of particles with size of 10^{-3} m, emissivity of 1 and density of 1000 kg.m^{-3}. The origin of time in the solar nebula is chosen arbitrarily. It can be seen that, at a given heliocentric distance, the ratio of F_{ph} to F_D decreases with time. Moreover, the equilibrium between F_{ph} and F_{rad} to F_D on particles is reached at the heliocentric distance of 50 AU after ~3

Myr of the disk's evolution. With time, the equilibrium region moves inwards and reaches the heliocentric distance of ~30 AU before the dissipation of the solar nebula.

Note that the actual precise location and time of the transition region is dependent on the particular solar nebula model we use. However, what ever the model we use, the transition region appears always at roughly the same place. In addition, although it looks like the transition region may be very far from the Sun at the early stages, this may not be the case as the solar nebula will become optically thin only after some time has elapsed. The final location of the transition region is also a strong function of the solar nebula dissipation mechanism (photoevaporation here).

Implications for comets: After several millions of years of evolution, the solar nebula becomes optically thin and crystalline silicates particles are transported by photophoresis in the outer part of the disk. At this epoch, comets were already formed in the outer solar nebula [10] and it can be expected that their sources populations were not yet ejected from their formation zones by the migration of Neptune. In these conditions, from Fig. 1, it can be seen that comets orbiting beyond 30 AU will first meet the belt of crystalline silicates particles. With time and during its inward migration, the particles belt is progressively emptied due to the continuous collisions with the multiple orbiting comets. Hence, it can be inferred that comets formed below 30 AU will meet a depleted belt of crystalline silicates particles. This mechanism implies that comets formed at lower heliocentric distances should be poorer in crystalline silicates than comets formed at higher distances in the solar nebula. This statement is fully compatible with recent observations of several comets [3].

Moreover, we note that crystalline silicates supplied to comets via photophoresis should be contained in an outer dusty shell surrounding the cometary core. In the case of a transport by turbulent diffusion, the crystalline silicates should be homogeneously mixed with the other compounds within the cometary core.

Finally, one must note that if the optical thinning of the nebula progressively occurred from the inside out, then photophoresis may create a dusty ring that would move slowly outwards. This ring would be located at the boundary region between the optically thick and thin parts of the disk and would follow its motion. As a result, this could give additional silicate mantling to cometary bodies formed closer than 30 AU.

This work was supported in part by the Swiss National Science Foundation.

References: [1] Campins & Ryan (1989) ApJ 341, 1059. [2] Crovisier et al. (2000) Science 275, 1904. [3] Sitko et al. (2004) ApJ 612, 576. [4] Harker & Desch (2002) ApJ 565, 109. [5] Bockelée-Morvan et al. (2002) A&A 384, 1107. [6] Krauss & Wurm (2005) ApJ 630, 1088. [7] Wurm & Krauss (2006) Icarus, in press. [8] Shakura & Sunyaev (1973) A&A 24, 337. [9] Alibert et al. (2004) A&A 417, 25. [10] Weidenschilling (1997) Icarus 127, 203.