THE FUNDAMENTAL ROLE OF PHOTOPHORESIS FOR DUST IN PLANETARY SYSTEMS

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ABSTRACT

There are two major sources of interplanetary dust in the Solar System: comets and asteroids. Since most of the short period comets are assumed to originate from the Kuiper belt, dust might eventually be traced back to two ring-like reservoirs – the Kuiper belt and the asteroid belt. We have recently found that photophoresis in a late Solar Nebula might explain exactly that – the formation of belts. Based on the only assumption that a transparent, yet gas rich protoplanetary disk existed, a concentration of solid matter in ring-like structures seems inevitable. In particular, the position of the ring(s) depends on the disk model and on the thermal, optical, and surface properties of the particles. While dust aggregates are concentrated several tens of A.U. away from the Sun, chondrules, which are found in primitive meteorites, are concentrated a few A.U. away from the Sun. This suggests that (primitive) asteroids and comets or Kuiper belt objects form rather late in protoplanetary disks by photophoretic concentration.

1. PHOTOPHORESIS IN PROTOPLANETARY DISKS

Studies on the topic of photophoresis have been published for longer than a century now [1, 2, 3, 4]. It is thus, well established, both experimentally and theoretically. The photophoresis effect, which can be traced back to the work of Sir William Crookes and Heinrich Geißler [1, 5], can be nicely illustrated with radiometers commonly known as light mills. In short, photophoresis is a force imposed on a particle by light in a gaseous environment. It is not to be confused with radiation pressure. Photophoresis is based on momentum transfer from gas molecules to a particle with temperature gradients across its surface. Photophoresis can be many orders of magnitude larger than radiation pressure forces.

Curiously, however, few applications have emerged from the effect. This is probably due to the fact that photophoresis is a feeble, and therefore inconspicuous effect at atmospheric pressure (1 bar). Even at low pressures and at intense optical radiation, gravity and friction are still usually dominating the accelerations on a dust particle in an Earth-bound environment. However, photophoresis by sunlight in the Earth's stratosphere can levitate dust particles [6], which currently finds a renewed interest. Also, only recently, photophoresis has been considered in the context of window-cleaning, and the effect is exploited for applications on the International Space Station [7, 8].

Otherwise, photophoresis has been ignored in astrophysics or planetary science up to now. As techniques improve in theoretical and observational astronomy, it seems clear, at least in protoplanetary disks at certain times, that the conditions enabling the process of photophoresis to occur, do exist. Photophoresis might be fundamental to the formation of comets and asteroids, as was discussed in detail recently by Krauss and Wurm [9] and Wurm and Krauss [10].

Shortly after they are formed, protoplanetary disks are optically thick [11], eventually becoming transparent to visible light, after a few million years. The exact timescale depends on the timescale of the evolution of the solids, i.e., of the dust fraction within the disk. It is important to note that the dust and gas develop differently, and at different timescales, due to different processes. While the dust grows to planetesimals and protoplanets, the gas remains essentially unchanged; recent observations suggest for as long as 10 million years [13]. The gas content changes only later, e.g. when it is dispersed due to stellar winds etc. [12]. If the gas remains unchanged for a significant time, then there could be a late time in the protoplanetary disk development, when the disk is transparent to visible radiation, but, at the same time, it contains a quantity of gas that is close to its original. It is inevitable that photophoresis will work on any solid particle that is embedded in the disk. We remind the reader that photophoresis has only two requirements, gas and light.

A transparent disk still contains small particles because they are continuously produced in the collisions of larger objects [14]. What will photophoresis do to such particles? To quantify the effect, we consider spherical particles, which we assume to absorb the light completely at their surface. The photophoretic force for low gas pressure (a free molecular flow regime) is given as [3]:

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$$F_{Ph} = \frac{\pi a^2 I p J_1}{3k_{th}T/a + 12\sigma T^4 \varepsilon + p(18kT/\pi m_g)^{1/2}} \,. \quad (1)$$

Here, the particle parameters are the particle radius a, the thermal conductivity k_{th}, and the emissivity ε. The gas parameters are temperature T, molecule mass m_g, and pressure p. Additional parameters are the radiative flux of the light source I and the asymmetry parameter J_1, which characterizes the accommodation of gas molecules at the surface and the absorption of light. Accomodation refers to the fraction of gas molecules which impinge a surface, stick for a while, and are then rejected diffusely according to the surface temperature. For complete absorption of light and a 100% accommodation of the gas molecules, J_1 = 0.5. The Boltzmann constant is k = 1.38 10^{-23} J K^{-1}, and the Stefan-Boltzmann constant is σ = 5.67 10^{-8} J K^{-4} m^{-2} s^{-1}.

The photophoretic force depends on the gas pressure, which varies throughout the disk. Assuming a gas density, which decreases with distance to the star, the photophoretic force will be strongest closest to the star, and decreasing in strength outwards. An important process in a transparent disk is an inward drift of the solids, in opposition to the photophoretic outward motion, due to the fact that the gas, to which the small particles are coupled, is rotating slightly slower than the Keplerian speed. Even though the gas is supported by the pressure gradient, the solid particles are not, and they therefore feel a residual gravity, which pulls them inward [15]. Inward particle drift is often considered a problem in optically thick protoplanetary disks because this drift can quickly remove particles, as they migrate into the star. Fig. 1 shows a simple sketch of the opposing forces: residual gravity and photophoresis.

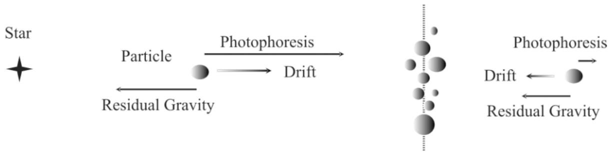

Figure. 1 Ring formation by photophoresis.

Close to the star, photophoresis is dominating and particles drift outwards. While the absolute magnitude of both forces decreases further out, photophoresis decreases faster, due to its gas pressure dependence. The result are particles close to the star moving outwards, while particles at large distances from the star drifting inwards. Consequently, at a particular distance, both forces are in equilibrium and the particles move in stable orbits. As can be seen in Eq. 1, photophoresis depends on the particle volume (mass), as long as the particles are small and the second and third term in the denominator can be neglected. Since gravity also depends on mass, the ratio between inward-directed and outward-directed forces is initially independent of size. Thus, the same kinds of particles (same thermal conductivity, optical properties) are concentrated at the same distance, resulting in the formation of a ring of solids.

2. DUST RINGS IN EXTRASOLAR SYSTEMS

Many observed young circumstellar sources display a ring-like structure. An example is HR 4796A [16] (Fig. 2.). As described previously, the photophoresis effect can explain dust rings. It is worth asking if photophoresis can also *quantitatively* explain their position. Fig. 2 displays the result of calculations of the equilibrium position in HR 4796A for typical assumptions.

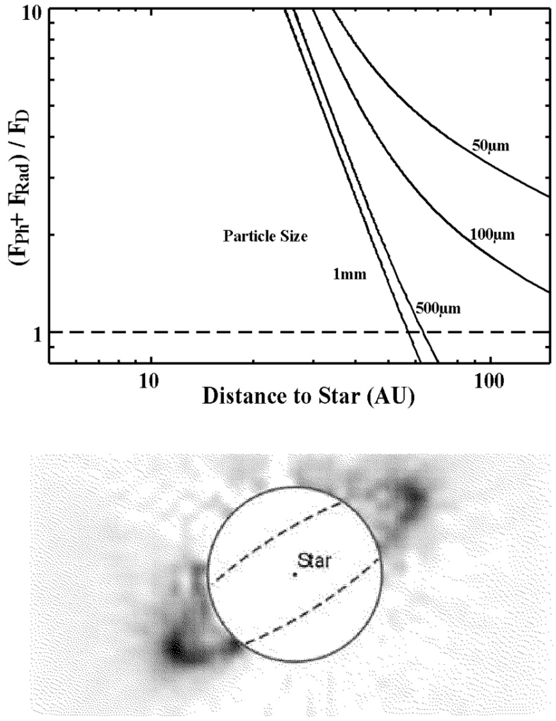

Figure. 2 Photophoretic force and radiation pressure over gravity. A ring forms at a ratio of 1 at 60 to 70 A.U. from the star. This is in agreement with HST observations of HR 4796A shown below.

A ring would naturally form at 60 to 70 A.U., which is in perfect agreement with the observations. Further details can be found in Krauss and Wurm [9]. Here, the system might currently have too little gas for photophoresis to be effective. However, if at some time in the recent past, photophoresis did concentrate particles into a ring, then a growth of larger bodies is almost another inevitable consequence [15, 17]. Dust which is seen now would then be not the direct observation of photophoretic concentration, but instead be the production from collisions of larger objects, which formed a little earlier at this position.

It is a consequence of the dust particles' concentration, that larger bodies grow proportionally to the enhancement of the particles' collisional frequencies. If, during the times of the optically thick disk, the growth of large bodies took place with nonphotophoretic processes, then photophoretic concentration might "only" locally boost the bodies' growth to still larger sizes, or else add "outer shells" of dust, which could bear the signatures of dust from the inner planetary system [18]. If, however, the number density of solids was previously not high enough to achieve particle growth, then the concentration of dust by photophoresis might itself initially trigger the formation of the larger bodies.

3. KUIPER BELT AND COMETS IN THE SOLAR SYSTEM

The same mechanism for dust concentration also applies to dust in the late (transparent) Solar Nebula. The differences to the previously-discussed case of an extrasolar system are the star's luminosity and the nebula's gas density. If we assume a solar luminosity and a gas density according to the minimum mass Solar Nebula by Hayashi et al. [19], then a dust concentration results at a distance of 30 A.U. In a slightly more massive disk, the dust would drift into the region, which is known today as the Kuiper belt [8]. Here, as above, it is likely that the growth of larger bodies results from the dust's concentration and subsequent collisions. Such a formation mechanism has implications on the composition of cometary dust. It was once assumed that comets are dirty snowballs with more ice than dust. Now, this picture is shifting, e.g., from the recent results of the Deep Impact mission for comet 9P/Tempel, which indicates at least as much dust as ice [20]. If dusty material was effectively transported outwards by photophoresis, then it should be expected that a larger fraction of dust was eventually built into most comets and Kuiper belt objects. Another implication in cometary dust regards crystalline silicates, which have been observed in comets [21]. Photophoresis can easily move crystalline silicates from the Solar Nebula's inner regions, where they likely have formed, to the outer comet-forming regions of the system.

4. PRIMITIVE METEORITES AND ASTEROIDS

The photophoretic force given in Eq. 1 depends on the thermal conductivity of the material k_{th}. Dust aggregates considered so far are exceptionally well-insolating. Thus, their thermal conductivities can be as low as k_{th}=0.001 W/mK [22]. Primitive meteorites show another distinct kind of particle, chondrules, which are (sub)-mm-sized spherical particles, which were formed by flash melting in the early Solar Nebula [23]. In contrast to aggregates of dust particles, chondrules have higher thermal conductivities, which determine the equilibrium position (see Eq. 1). If we assume thermal conductivities of about 1 W/mK in a minimum mass Solar Nebula, then the concentration of chondrules would be located at about 3 A.U. from the Sun, which is within the current Main (asteroid) belt. By removing aggregates, which were built only from the dust at the same time, the photophoresis mechanism might explain the high concentration (60% of the volume of a chondrite [23]) of chondrules. A photophoretic concentration of chondrules has other advantages over other mechanisms of concentrating chondrules, as well. For small aggregates of chondrules, the equilibrium position does *not* depend on the overall size of the aggregates, but *does* depend on the size of the individual chondrules. Thus, by this mechanism, chondrules are size-sorted, a phenomenon which has been seen in chondrites [24]. The size-sorting mechanism that was most highly-regarded before, aerodynamic sorting, fails as soon as chondrules stick together.

Another chondrite fact to consider is the age difference of the chondrules, which might be 1 million years or more, all found within the same chondrite. Such a large age difference does not fit the chondrules' individual dwell-times in the Solar Nebula; they inevitably collide with other particles and grow into larger bodies in a short time, for example, into km-size objects within a few thousand years [15]. Thus, chondrule concentration and sorting could occur after larger bodies have already formed. Then, later on, chondrules could have been easily extracted from the larger bodies by collisions [14]. Such a scenario places the formation of chondrites at a later, more reasonable time, when the disk was transparent. Therefore, chondrites would not be primitive solar system relics. Indeed, recent research on iron meteorites indicates that the formation of differentiated bodies was quick, predating the formation of the chondrites [25].

We note that the real photophoretic properties of chondrules and chondrule-dust mixtures might differ significantly from our assumptions. Photophoretic forces might differ in strength and, in extreme cases, in direction, but this is a complex problem that requires more attention in the future. A somewhat more detailed treatment on the photophoretic concentration and sorting of chondrules can be found in [10].

5. IMPLICATIONS FOR DUST IN PLANETARY SYSTEMS

Certainly, photophoresis plays a limited role for the motion of a dust particle in the current, essentially gas-free Solar System. However, it might have been a major factor for – if not triggering – the formation of the two most important dust reservoirs in the Solar System – comets and the asteroids. With a likely participation of photophoresis in the formation of these and other dust reservoirs, it is vital to understand the process and its selection process in more detail.

As previously mentioned, some features of comets might be the natural result of photophoretic concentration, as material moved outwards from the inner Solar System. First attempts to correlate the observed features of crystalline silicates in cometary dust to photophoretic migration during the formation of comets, seem to be quite promising [18]. Another promising feature is a higher dust-to-ice ratio [20], since particles that moved from the inner to the outer solar system would be solid, rather than icy. Implications follow for the structure of cometary dust aggregates; a more compact skeleton would remain after the ice has sublimated. Being more compact would also change the cometary dust's optical properties. Finally, the relative contributions of asteroids and comets to the total dust produced in the solar system would also be affected.

These are just a few immediate consequences of the effect of photophoresis which – unnoticed until today – might once have been fundamental to the Solar System formation.

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