Meteoritics & Planetary Science 44, Nr 5, 689–699 (2009)
Abstract available online at http://meteoritics.org

Outward transport of CAIs during FU-Orionis events

Gerhard WURM[1*] and Henning HAACK[2]

[1]Institut für Planetologie, Wilhelm-Klemm-Str. 10, D-48149 Münster, Germany
[2]Center for Stars and Planets, Natural History Museum of Denmark, University of Copenhagen, Øster Voldgade 5-7, DK-1350 Copenhagen K, Denmark
*Corresponding author. E-mail: gwurm@uni-muenster.de

(Received 10 September 2008; revision accepted 19 February 2009)

Abstract–Evidence from meteorites shows that the first solids to form in the solar system, calcium-aluminum-rich inclusions (CAIs), were transported outward from the Sun by several AU in the early solar system. We introduce a new concept of levitation and outward transport of CAIs at the surface of protoplanetary disks. Thermal radiation from the disk and the Sun can cause particles to levitate above the disk and drift outward through a process known as photophoresis. During normal conditions this process only works for dust-sized particles but during high luminosity events like FU-Orionis outbursts, the process can provide an efficient lift and transport of CAIs from within the inner 1 AU to a distance of several AU from the Sun. This might explain why CAIs, believed to have formed close to the Sun, are common in meteorites believed to come from the outer asteroid belt but are rare or absent in samples from the inner solar system. Since the process only works during the FU-Orionis event and only for particles up to cm-size, it may also explain why the CAIs we find in meteorites appear to have formed within a short period of time and why they rarely exceed cm size.

INTRODUCTION

Transport processes occurring in protoplanetary disks govern the formation of asteroids, comets, and planets. Gas constitutes most of the disk mass and since the disks are assumed to be turbulent in large parts this leads to efficient viscous accretion onto the central star (Balbus and Hawley 1991). Typical accretion rates in turbulent protoplanetary disks around solar type stars are 10^{-7} M_S/yr declining with time (Armitage et al. 2003; Alibert et al. 2005). Average inward drift speeds related to the accretion are up to several cm/s. Due to gas-grain coupling this motion will also be superimposed on any motion of small solid particles in the disk. However, at 1 cm/s particles only move 2 AU in 1 million years which in most cases is small compared to other drift motions. As time proceeds the solids evolve in size. The initial evolution of solids will lead to growth of cm-size aggregates which settle to the midplane of the disk in a few thousand years (Blum and Wurm 2008). Bodies larger than cm-size are essentially confined to the midplane region. Planetesimal formation and the subsequent formation of asteroids and comets are supposed to proceed in the midplane of the disk.

The evolution of the disk and its solids is also important for the optical appearance of the disk. Small particles efficiently render the disk optically thick to visible radiation. The initial population of (sub)-micron dust particles will lead to an optical surface of the disk at about 4 to 5 pressure scale heights (Watanabe and Lin 2008). However, as particles evolve, grow and sediment, the surface will decrease in height and can reach down to 1 pressure scale height (Chiang et al. 2001).

Typically, the formation of larger objects is discussed in the framework of a static or slowly evolving protoplanetary disk surrounding a solar type star with constant parameters, i.e., constant luminosity (Weidenschilling and Cuzzi 1993; Alibert et al. 2005; Brauer et al. 2008; Johansen et al. 2008). However, young stars with protoplanetary disks are believed to go through phases of increased luminosity in FU-Orionis outbursts (Herbig 1977; Bell and Lin 1994; Hartmann and Kenyon 1996; Malbet et al. 2005). As mass accretion rates increase to 10^{-4} M_S/yr the luminosity of the central region increases by a factor of 100 on a short time scale but the luminosity declines on time scales of a few 100 years. The range of time scales and number of outbursts for individual stars is uncertain. Here, we consider the possibility of transport of solids in one FU-Orionis event.

As accretion is increased, the inward flow of gas is also increased up to several tens of m/s on average. However, as we will show the outburst still enables a very efficient photophoretic transport of up to cm-size particles from the inner disk to regions further out via flow along or above the optical surface of the protoplanetary disk. Evidence of such transport comes from solar system studies.

Samples of up to cm-sized particles that formed in the early solar system have been preserved in chondrites. They contain two main types of particles that formed in the nebula: Calcium aluminium rich inclusions (CAIs), and chondrules. These particles are embedded in matrix comprised of µm sized silicate-rich material (Scott and Krot 2006). With an age of 4567.2 Gyr the up to cm-sized CAIs are the oldest dateable objects that we know of (Amelin et al. 2002). CAIs are believed to have formed close to the Sun during a very short time-span of 20 to 100 ky (Itoh and Yurimoto 2003; Bizzarro et al. 2004, 2005). Presently, CAIs are mainly found in carbonaceous chondrites that appear to originate from the outer parts of the asteroid belt. A CAI has also been reported in the samples of comet Wild 2 brought back by the Stardust spacecraft (Zolensky et al. 2006). CAIs must therefore have been transported up to at least several AU outward within the first few million years after the solar system formed.

CAIs carry a distinct ^{50}Ti anomaly which may be used to estimate their abundance in the source material for differentiated asteroids and planets (Trinquier et al. 2007). Absence of the anomaly in the Earth, Moon, and Mars and most differentiated meteorites suggests that CAIs were not abundant in the inner solar system when these objects accreted. The CAIs are, in other words rare in the regions where we believe they formed but relatively common in a region ~3 AU further from the Sun.

The observed properties of chondrules and CAIs suggest that one or more outward transport mechanisms were active in the early solar system. It was suggested that such a transport could be facilitated by an outgoing flow of gas near the midplane of the disk (Takeuchi and Lin 2002; Ciesla 2007). Other prominent mechanisms proposed so far have been the X-wind model (Shu et al. 1996) or outward transport in jets (Liffman 2005).

Whatever the nature of the mechanism was, it delivered particles that had formed in a very short time span, with a very restricted size range from a location close to the Sun to a distance of several AU from the Sun. Although we cannot tell if the particle properties should be attributed to the transport mechanism and/or the formation process we will show that transport by photophoresis may potentially explain several key properties of CAIs.

Our model assumes that recently formed CAIs are present close to the Sun at the onset of an FU-Orionis event. This could either be because the FU-Orionis triggers formation of CAIs or because CAIs form continuously but have limited lifetimes in the nebula. In that case we only see those that are transported outward during the FU-Orionis event.

LEVITATION BY PHOTOPHORESIS BASED ON THERMAL RADIATION

Since the properties of chondrules and CAIs indicate that they formed in the presence of the nebula, any transport mechanism that involves gas and/or radiation may have been active. Photophoresis is a potentially powerful effect acting on particles in a gas that are exposed to radiation (Rohatschek 1985; Beresnev et al. 1993). It is a force acting on a particle which is illuminated and absorbs light. This absorption leads to a temperature gradient within the particle. If the particle is embedded in a gas, the particle is subject to a force directed from the warm to the cold side, due to the interaction with the gas molecules. Simple estimates already show that the photophoretic force on small particles in transparent parts of protoplanetary disks can be larger than the gravitational attraction of the star (Krauss and Wurm 2005; Wurm and Krauss 2006). Therefore, the dynamical behavior of particles in illuminated parts of the disk cannot be treated without including photophoresis.

A rigorous treatment of photophoresis on spherical particles of radius a for all gas pressures, i.e., in the free molecular flow regime and the continuum regime, has been given by Beresnev et al. (1993). Assuming the accommodation coefficients (how gas molecules on the surface of a particle adapt to energy and momentum) to be 1 and a complete absorption of the light at the illuminated side of the particle, the photophoretic force is given as (Beresnev et al. 1993)

$$F_{ph} = \frac{\pi}{6}a^2 I\left(\frac{\pi m_g}{2kT}\right)^{1/2}\frac{\Psi_1}{1+\Lambda\Psi_2} \tag{1}$$

where I is the light flux, m_g is the average mass of the gas molecules (3.914×10^{-27} kg), T is the gas temperature, k the Boltzmann constant, and ψ_1 and ψ_2 are functions of the Knudsen number (Equation 3). The particle's thermal relaxation properties which determine the temperature gradient throughout the particle are expressed in the heat exchange parameter

$$\Lambda = \frac{\lambda_P + 4\sigma T^3 a}{\lambda_g} \tag{2}$$

where λ_g is the thermal conductivity of the gas, λ_P is the thermal conductivity of the particle, and σ is the Stefan-Boltzmann constant. The second term in the numerator accounts for the thermal emission from the particle's surface assuming an emissivity of 1. The functions ψ_1 and ψ_2 in Equation 1 depend only on the Knudsen number Kn, which is the ratio between the mean free path of the gas molecules and the particle radius a (Beresnev et al. 1993)

$$\Psi_1 = \frac{Kn}{Kn + (5\pi/18)}\left(1 + \frac{2\pi^{1/2}Kn}{5Kn^2 + \pi^{1/2}Kn + \pi/4}\right)$$
$$\Psi_2 = \left(\frac{1}{2} + \frac{15}{4}Kn\right)\left(1 - \frac{1.21\pi^{1/2}Kn}{100Kn^2 + \pi/4}\right) \quad (3)$$

Keeping in mind that the absorption of light and accommodation of gas molecules were assumed to be perfect only 2 particle properties remain to enter in Equation 1, which are

- Particle radius a
- Thermal conductivity of the particle λ_P

So far, work on photophoresis in protoplanetary disks has considered the force imposed on particles by stellar radiation and in the midplane of protoplanetary disks (Krauss and Wurm 2005; Wurm et al. 2006; Wurm and Krauss 2006; Krauss et al. 2007; Mousis et al. 2007; Wurm 2007; Herrmann and Krivov 2008; Takeuchi and Krauss 2008). This is restricted to disk configurations where stellar radiation illuminates the particles and is important at the inner edge of the disk and at (late) times when the disk overall has become transparent. Here, we do not require the disk to be optically thin as we consider transport at the surface of the disk. Per definition the surface of the disk marks the transition between an optically thick lower disk and an upper disk region, which is transparent to optical and infrared radiation.

It is important to note that we consider two different radiation sources here. One is the radiation of the central source with about 100 times solar luminosity during the FU-Orionis outburst. The second radiation source is the protoplanetary disk itself, which emits thermal radiation mostly at infrared wavelengths. Photophoresis only depends on the ability of a particle to absorb radiation. Therefore, the optical radiation as well as thermal radiation can induce a photophoretic force. In detail the strength and direction of photophoresis depend on the optical and thermal properties of the particle (i.e., albedo, morphology, shape, thermal conductivity tensor). For the model discussed here we assume that all radiation incident on a particle will be absorbed completely at the illuminated side of a spherical, homogeneous particle and particles move in the direction of illumination. While this is a simplification the principal results of the model at the current level of uncertainties within the disk model do not depend on this. We note that even irregular dust aggregates with complex geometry are still essentially accelerated in the direction of light as we have recently studied in microgravity experiments (Wurm et al. unpublished). We therefore assume that our results also hold for irregular CAIs. Particle rotation can change the thermal structure within a particle and in extreme cases of fast rotation might decrease the efficiency of photophoresis. However, as particles are embedded in a gas, random rotation is damped quickly and rotation is not an issue which will prevent photophoresis. A detailed discussion on rotation can be found in Krauss et al. (2007).

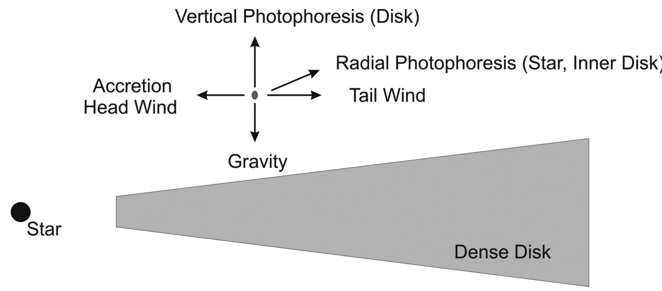

Fig. 1. We consider a particle at higher levels within the disk to be subject to different forces: gravity towards the midplane, accretion flow, inward drift due to the sub-Keplerian motion (head wind) or a tail wind due to super-Keplerian rotation, photophoresis by thermal radiation from the disk surface (vertical photophoresis), and photophoresis by stellar radiation and radiation from the hot inner part of the disk (radial photophoresis). Radiation pressure is added to photophoresis in the same directions.

To distinguish the two light sources of importance here we will further call photophoresis induced by the light from the central region *radial photophoresis* as its main component is in the radial direction. We term the photophoresis induced by the thermal emission of the disk *vertical photophoresis* and for simplicity we will assume it to act in the vertical direction only. The forces acting on a particle are illustrated in Fig. 1.

In general, for the particles considered here, photophoresis is directed away from the radiation source, which at the surface, is upwards and away from the star. The lift due to vertical photophoresis vanishes far below the surface where thermal radiation might be considered to be isotropic. However, once a particle is above the dense disk photophoresis will push it upwards where it becomes exposed to radial photophoresis and pushed away from the Sun.

FU-ORIONIS DISKS AND CAIS

Models of FU-Orionis outbursts suggest that the increase in luminosity of the system is due to an enhanced accretion rate within the inner 1 AU of a protoplanetary disk. The purpose of our model is to determine if the increased radiation (optical and infrared) will provide a sufficient photophoretic force to lift and transport CAIs outwards by several AU. To implement a photophoretic force we need to choose a model for the basic variables entering in the calculations (Equation 1). The basic variables of a particle's environment needed to calculate the photophoretic forces are

- Light flux I
- Gas pressure p
- Gas temperature T

Our model assumes the star to have 100 times the present solar luminosity though we also vary this parameter. While this is not quite correct as the accretion energy might be released by disk radiation, most of the energy is released by the very inner disk close to the star and the light source can still be viewed as a central object with 100 times solar luminosity. The luminosity controls the temperature of the disk. The thermal irradiance to be used to calculate the vertical photophoretic lifting force is then simply given by

$$I_{\mathrm{thermal}} = \sigma T^4 \tag{4}$$

which, for simplification, assumes that the radiation is in the vertical direction. To specify pressure and temperature we choose a simple power law disk model. The power and temperature distribution are taken from Hayashi et al. (1985) but as this is a minimum mass nebula and as FU-Orionis outbursts occur at early times we assume the disk to be a factor 10 more massive. We further extend it inward to 0.3AU.

$$\rho_{\mathrm{mid}} = 1.4 \cdot 10^{-5}\left(\frac{R}{1\mathrm{AU}}\right)^{-\frac{11}{4}} \mathrm{kgm}^{-3} (R \geq R_i) \tag{5}$$

$$\rho = \rho_{\mathrm{mid}} e^{-\frac{1}{2}\left(\frac{z}{h}\right)^2}$$

$$T = 280\left(\frac{L_{\mathrm{Star}}}{L_{\mathrm{Sun}}}\right)^{\frac{1}{4}}\left(\frac{R}{1\mathrm{AU}}\right)^{-\frac{1}{2}} \mathrm{K}$$

$$\rho = 5 \cdot 10^{-2} T\left(\frac{R}{1\mathrm{AU}}\right)^{-\frac{11}{4}} \mathrm{Pa}$$

where ρ is the gas density, ρ_{mid} is the midplane gas density. R is the radial distance to the star, z is the vertical height over the midplane, h is the pressure scale height, which we assume to be $h = 0.1\ R$ further on. Slight variations in the assumed scale height dependence on distance do not change the principle results here and do not significantly modify the absolute values of the particle drift. There is a difference in flared or non-flared disks though as discussed below. L_{Star} and L_{Sun} are the luminosity of the considered star and the sun, respectively. We cut off the disk at an inner radius $R_i = 0.3$ AU. No gas is assumed to exist further in. This assumption is not important for the suspension of particles at the surface by vertical photophoresis but it is important for the radial transport. We assume two cases here. First, we take an opacity of 5×10^{-4} cm^2/g. This is an appropriate value for Rayleigh scattering by molecular hydrogen (Dalgarno and Williams 1962). This value is modeling the situation that the disk profile is indeed as modeled (scale height proportional to the distance to the star). It assumes that all gas between the inner edge of the disk and the position of a particle attenuates the light intensity. We do not consider opacities determined by dust as we are interested in particle motion at the surface of the disk, assuming the CAIs are within an optical thin layer in radial direction on top of other dust layers. This is partly justified by the results presented below.

Another extreme would be a flared disk where the scale height does not increase linearly with distance to the star but stronger. Such a profile was e.g., assumed by Lachaume (2004) to model FU-Orionis disks. Lachaume (2004) explicitly assumed that in a curved geometry light from the central source reaches the surface of the disk further out. In that case light is not attenuated by travel through the disk. While our simple disk model does not account for possible flared geometries we model such a case by assuming that the particles at the surface are illuminated by full intensity from the inner region without extinction of the light.

There are some additional forces acting on the particle. One force is the gravitational component of the star toward the midplane of the disk, which counteracts levitation by thermal radiation. The disk itself is assumed to have a negligible gravitational attraction on the particles.

Important for the radial transport besides photophoresis is a potentially fast inward drift which can result from the increased accretion as long as CAIs are entrained in the accreting part of the disk. Bell and Lin (1994) suggest that high accretion in FU-Orionis is only restricted to the very inner annulus of the disk of several stellar radii, which is highly accreting episodically, namely during FU-Orionis phases. Further out the disk is supposed to have a continuous moderate accretion rate. We adopt this view for our calculations below. To estimate the inward flow in the highly accreting part close to the star, we assume the disk accretes at a rate of $M' = 10^{-4}\ \mathrm{M_S/y}$. At $R = 0.5$ AU from the star the surface density is $\Sigma = 50\ \mathrm{kg/cm^{-2}}$ in our model and the vertical average of the drift velocity is $v = M'/(2\pi R\Sigma) = 27$ m/s. This is depending on the disk model. Larger densities result in smaller accretion velocities. The accretion event might be correlated to a local increase in mass, e.g., by a disturbance from a passing star (Reipurth 2003). In this case the surface density would also increase locally and the drift rate would further decrease. In any case, if accretion is restricted to the inner half AU and if particles are launched close to the star the photophoretic outward motion has to be larger than several tens of m/s to move particles outward.

Once the particles have escaped the inner rapidly accreting part of the disk they are only subject to accretion at a moderate rate. In detail the gas flow velocity varies with elevation and differs from the average accretion flow. Inward and outward gas flow is possible (Takeuchi and Lin 2002; Ciesla 2007). At the midplane of the disk the pressure decreases with distance from the Sun. The pressure gradient therefore supports the gas and causes it to rotate at sub-Keplerian speed. At higher elevation the horizontal pressure gradient reverses (Takeuchi and Lin 2002), causing the gas to rotate at super-Keplerian speed. As a result, the orbital velocity of the gas increases with height. If we include viscosity of the gas, the slowly rotating gas at the midplane will be forced to rotate faster than the equilibrium speed and thus drift outward whereas the fast rotating gas at high elevation is slowed down and thus drifts inward toward the Sun. This results in an outward drift of gas at the midplane and inward drift at high elevation.

The picture is more complicated for the solid particles. The absolute motion of a particle is the superposition of the gas flow to which the particles couple and the drift relative to the gas. Particles are not supported by the pressure gradient. Therefore, they spiral into the Sun if they are slowed down below Keplerian speed or spiral outward if the gas causes them to rotate super-Keplerian. Very small particles can be transported outward close to the disk midplane as the outward flow of gas dominates inward drift (Ciesla 2007). However, for larger particles (> mm) the net effect of gas outflow and particle inward drift is an inward drift (Weidenschilling 1977; Takeuchi and Lin 2002).

At the surface of the disk the particles do not drift inward. While the gas flows inward, the net effect at large heights is that particles move outward in parts of the disk which accrete moderately (Takeuchi and Lin 2002). Except for the smallest particles we therefore see an inward drift of particles at the midplane and an outward drift at high elevation—opposite to the gas drift (Takeuchi and Lin 2002). In a minimum mass solar nebula Takeuchi and Lin (2002) get outflow of 1 mm particles above 1.5 scale heights at 10 AU distance to the star. Particles rapidly reach outflow velocities of more than 10^{-5} AU/yr (~0.1 m/s) at larger heights. Therefore, if particles are capable of being levitated at the surface they can continue to flow outwards. The case of an average inflow is therefore not necessarily an obstacle to outward flow if the particles are high enough above the midplane and avoid intermediate heights. This is exactly what vertical photophoresis can accomplish. However, if time scales of FU-Orionis outbursts are only 100 yr, then the total drift caused by the tail wind is only about 0.001 AU while the outburst lasts. This is insignificant for large scale transport on the short time scales discussed here and we therefore do not consider other drifts but photophoresis further.

It might be worth comparing the effect of photophoretic drift to dynamics in the current solar system. It is well known that radial forces like e.g., radiation pressure are not able to push particles outward in the current solar system. They only induce an elliptical motion at reduced orbital velocity compared to a pure Keplerian rotation. This has frequently been confused with particle motion in protoplanetary disks as it seems to be in contrast that a radial force really leads to a radial drift. Radial motion in protoplanetary disks is due to the fact that the particles are embedded in a gaseous environment. The small particles considered couple to the gas on time scales much shorter than the orbital time scale. Therefore, the motion of a solid particle is not a free Keplerian motion but the rotation is bound to the gas (see discussion of radial drift by head wind and tail wind above). Any radial force like photophoresis induces a radial drift then and changes the distance of a particle to the star (Weidenschilling 1977). We calculate the drift velocities as

$$v = \frac{F}{m}\tau . \tag{6}$$

F is the force acting on the particle, m is the particle mass. As particle density we take $\rho_p = 2.5$ g/cm^3. The gas-grain coupling time is τ, which is given as

$$\tau = \frac{m}{6\pi\eta a}C . \tag{7}$$

Here, η is the gas viscosity, C is the Cunningham correction factor accounting for the different flow regimes and is given as (Hutchins et al. 1995)

$$C = 1 + Kn\left(1.231 + 0.47e^{\frac{1.178}{Kn}}\right) . \tag{8}$$

Figure 2 shows the radial outward drift velocities due to photophoretic forces and radiation pressure at the equilibrium height. The equilibrium is at about 3 pressure scale heights where vertical photophoresis equals gravitation to the midplane. The radial velocity is always largest at this height due to the lower gas density and the intense illumination which goes with less opacity. Shown are velocities depending on particle sizes and distances to the star. The thermal conductivity of the particles is assumed to be 1 W/mK and a gas opacity of 5×10^{-4} cm^2/g is assumed to attenuate the light from the inner edge (0.3 AU) to the particle position.

Particles in the mm-size range are the fastest. Maximum velocities of 200 m/s can be reached close to the edge of the disk. Estimates given above for the average inward drift at 0.5 AU were 27 m/s. Therefore, essentially all particles up to 1 cm could be transported outward at the surface by photophoresis even against a strong inward flow. Even if the inner edge of the disk would be placed closer to the star at 0.1 AU, which increases the attenuation due to Rayleigh scattering, a particle, e.g., at 0.3 AU would still move faster outwards than the average accretion rate would pull it in. Therefore, particles at the surface can always escape an inward drag towards the star and rapidly move to the part of the disk which is accreting at a moderate rate.

There is a steep cut-off in the ability to be lifted for particles somewhat larger than 1 cm. This is due to the pressure dependence of photophoresis. Photophoresis only increases in strength with gas density if the particle is smaller than the mean free path of the gas molecules. At still higher gas density it decreases again. At 0.5 AU cm-size particles are reaching this transition at the maximum height.

With opacity being present the drift velocities rapidly decrease further away from the star. This trend is visible in Fig. 2. We clearly note that if extinction is present which

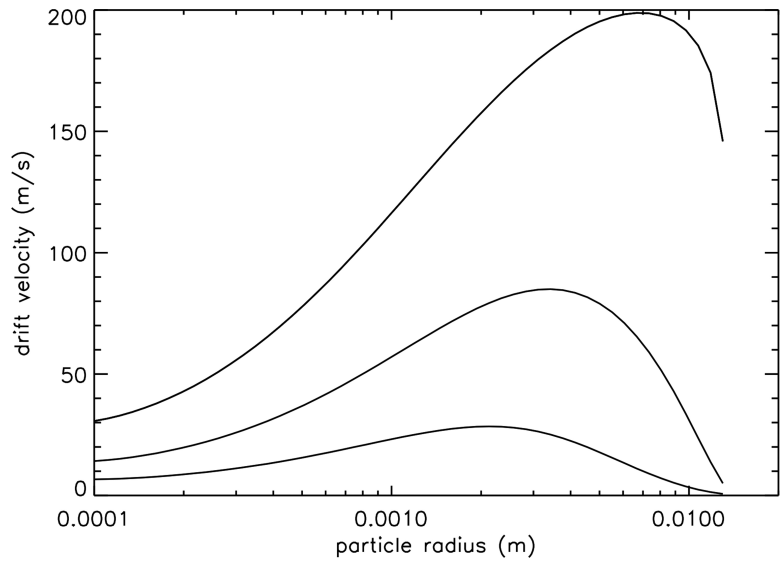

Fig. 2. Drift velocities for different particle sizes at the equilibrium height (≥3 scale heights above the midplane within the inner 1AU). From top to bottom the radial distance to the star is at 0.35, 0.5, and 0.65 AU. Thermal conductivities for all particles are 1 W/mK. Luminosity is 100 L_{Sun}. The opacity is assumed to be 5 10^{-4} cm^2/g.

inhibits an outward push by photophoresis then particles would get stuck at a distance somewhere within the inner 1 AU. While particles would still be levitated by vertical photophoresis and while particles flow outward at large heights (Takeuchi and Lin 2002), this would unlikely be effective as detailed above with a distance traveled of only 0.001 AU in 100 yr.

To push particles further outward, the radiation has to contain a significant radial component. One possibility is that the disk is flared like e.g., assumed by Lachaume (2004). Then the opacity assumed above is overestimated and light originating in the central region might interact with particles at larger distances essentially without extinction. Photophoresis then provides a continuous and strong outward directed force and can push particles to several AU in a short time.

In Fig. 3 drift velocities at the equilibrium corridor are shown for 5 mm particles depending on the distance to the star for two luminosities 100 L_S (solid lines) and 25 L_S (dashed lines). The light is assumed to have full strength simulating e.g., a flared disk. The different lines represent particles of different thermal conductivity, which are 1, 0.1, and 0.01 W/mK from bottom to top, respectively. The first would be representative for individual, monolithic particles, while the lower thermal conductivities can be reached for dust aggregates (Presley and Christensen 1997). They might simulate small CAIs which have been embedded in a dust aggregate somehow or which are aggregates of CAIs. In any case photophoretic drift velocities can easily reach several tens of m/s in the asteroid belt region which allows CAIs to be transported there and overcome even fast inward drifts. Fast outward flow is possible for aggregates even beyond 10 AU and allows particles to be transported to the comet forming region.

Figure 4 shows the drift of a 5 mm particle for different luminosities due to photophoresis for 500 yr drift time in a "flared" disk (no opacity). Particles are assumed to have a thermal conductivity of 1 W/mK. No other drifts are considered as we assume them to be much smaller. Particles are started at 1.5 scale heights at 0.5 AU from the star. As we assume no opacity, particles move outward as they rise and reach the equilibrium heights at about 1 AU.

The exact final destination of the particles depends on many details. Particles only move outward as long as the outburst takes place. If the luminosity drops drastically, e.g., back to solar, eventually dust aggregates of lower thermal conductivity will be lifted on top of the CAIs, and CAIs will become part of the optically thick disk and rain down. The drift phase then ends. As can be seen in Fig. 4 the equilibrium heights are decreasing with distance. The drift also ends if the levitation height decreases to a level that the surface is no longer below the transport corridor or if particles can no longer be considered to be in the flared, fully illuminated part of the disk. This might be considered as a final position which, again, depends on the exact situation of the disk.

In general particles will drift until the outburst is over or accumulate at a final position. Eventually, they all rain out, sedimenting to the midplane when the outburst is over. In any case outward transport to the asteroid belt region seems easily possible as the equilibrium is still at 2 scale heights for 100 L_{Sun}. As the drift velocity close to the star is much larger than at several AU, particles leave the inner region rapidly and the vast majority of the particles are transported several AU out. A strong concentration of CAIs at several AU results while the very inner region will be depopulated by CAIs and intermediate distances will only have a small number of CAIs.

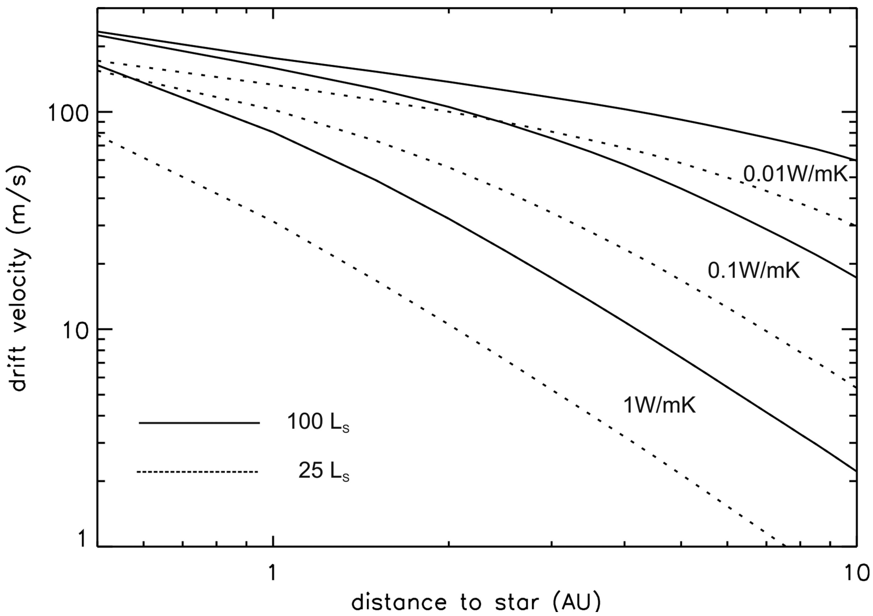

Fig. 3. Drift velocity for 5 mm radius particles depending on the distance to the star; solid lines: 100 L_S luminosity, dashed lines: 25 L_S luminosity, from bottom to top thermal conductivities are 1, 0.1, and 0.01 W/mK, respectively; radiation is not attenuated (flared disk).

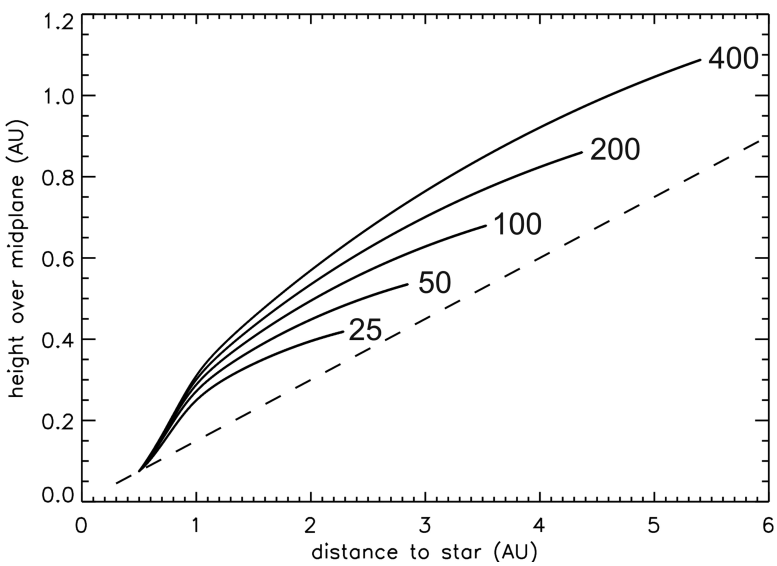

Fig. 4 Trajectories of 5 mm (radius) particles by photophoretic drift if no opacity is present (flared disk). Particles have thermal conductivity of 1 W/mK. Drift times are 500 yr. Luminosities are marked in units of solar luminosity. The dashed line gives 1.5 pressure scale heights.

Not shown here are particle trajectories for lower thermal conductivities as they would require a different radial scale due to much larger drift velocities (see Fig. 3). The CAI found in the stardust samples (Zolensky 2006) is therefore fully consistent with our model.

The high temperature at the inner edge of the disk and the free exposure to space above the disk will result in a very efficient vertical photophoretic transport of particles (Fig. 5). The model does not include shielding of radiation (or back warming) by other particles, i.e., on top of rising particles. This is justified near the inner edge of the disk where the rapid outward transport due to the radial photophoretic force from the Sun quickly removes the rising particles. If dust sized (micron) particles, which only move slowly, would originally dominate they will quickly be removed from the inner part of the disk by radiation pressure and thus give way to CAI-sized particles. The model assumes opacity for radial radiation due to Rayleigh scattering by hydrogen molecules or no opacity at all. Therefore, it assumes that the particles which rise to the surface are at an inner edge of solid particles and no solid particles exist further in. Particles further out would not be lifted if the inner parts are still filled with dust particles. The

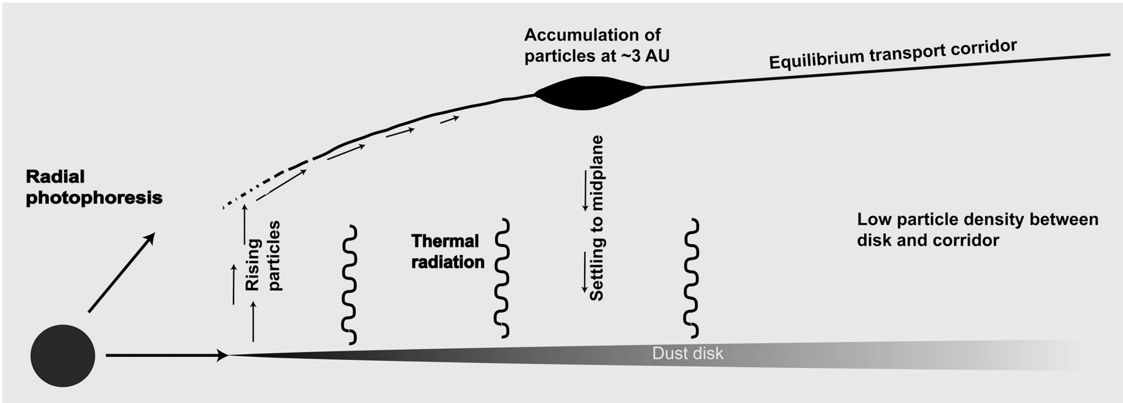

Fig. 5. The drift in the transport corridor results in accumulation at several AU, likely 3 AU in the solar system. Since particles at the lower part of the transport corridor will fall back if the temperature decreases with the decline of the FU-Orionis luminosity, particles will settle toward the midplane from the accumulation point.

lift of particles e.g., at 0.5 AU can only occur if particles further in have already been transported outward. Thus, only the innermost envelope of the solid particle disk is moved by photophoresis.

Protoplanetary disks are often assumed to have a flared geometry where stellar radiation can reach the surface of the disk without significant extinction. Lachaume (2004) explicitly considers the case of a self irradiated disk in the case of FU-Orionis outbursts. Per definition this assumes that the radiation of the central region is not significantly reduced. We therefore regard our model as a suitable way to describe the motion of particles, though more detailed analysis using a more realistic disk should be carried out in the future. If the disk is not flared, outward transport by photophoresis is not possible. It will still prevent particles from getting lost to the star but we are then essentially back to the result by Wurm and Krauss (2006) that photophoresis can keep CAIs alive in the disk.

We currently cannot restrict the light flux and outburst durations further, nor do we know how far the strength of the photophoretic force will deviate from our simplified assumptions. This allows for a wide variety of possible transport distances but some general features outlined above are clearly indicating that photophoretic transport over the surface of protoplanetary disks is indeed an active process in protoplanetary disks especially during outbursts.

In order to assess the significance of photophoretic transport we need to compare the amount that can be transported to an estimate of the amount of CAIs that were transported outwards. An estimate of the original mass of transported CAIs in the early solar system is $M_{CAI} = M_0 C_{CAI} A_C$ where M_0 is the original mass of the asteroid belt, C_{CAI} is the abundance of CAIs in carbonaceous chondrites and A_C is the abundance of the C-type asteroids where carbonaceous chondrites are believed to come from. The abundance of CAIs in carbonaceous chondrites is between ~0 and 13 vol% (Brearley and Jones 1998) or ~6 vol% on average. Carbonaceous chondrites are believed to come from C-type asteroids which at 75% are the most common type of asteroid we know of. The original mass of the asteroid belt has been estimated to be between 0.035 and 0.11 Earth masses (Bottke et al. 2005). This gives us an original mass of transported CAIs between 0.002 and 0.005 Earth masses.

The maximum mass density in the transport corridor is controlled by the opacity. In order to stay levitated, all of the particles need to be exposed to thermal radiation from below and exposed to empty space above.

Our models already give us an estimate of the radial velocity of CAIs in the transport corridors. In order to estimate the outward flux we need an estimate of the mass of CAIs in the transport corridors. The density of particles in the corridors is limited since each particle must be fully illuminated from below to stay levitated. Therefore, the total geometrical cross section of all the particles in a vertical column cannot exceed the cross section area of the column. Assuming that the particles in the column are spheres with radii r and density ρ, the maximum number of particles per unit area is $1/(\pi r^2)$. The mass of each sphere is $4/3\ \pi\ \rho\ r^3$. The total mass of particles per unit area is thus $4/3\ \pi\ \rho\ r^3/\pi\ r^2 = 4/3\ \rho\ r$. The outward flux of material through the corridors on either side of the midplane is equal to the mass density in the corridor times the radial velocity of the CAIs, v. The total mass transport at a heliocentric distance of R is thus $2\ 2\pi\ R\ v\ 4/3\ \rho\ r$. Using a heliocentric distance of 3 AU, a radial velocity of 10 m/s, a CAI density of 2500 kg/m^3, and a CAI radius of 0.5 mm we get a mass transport of $5\ 10^{-4}$ Earth masses/yr or 0.05 Earth masses in 100 yr.

Photophoretic drift therefore has the potential to transport an order of magnitude more CAIs during a 100-year FU Orionis event, than our estimate of the total amount actually transported.

There is a limit of about 1 cm where particles close to the star can no longer be lifted and transported. This somewhat depends on the stellar luminosity but the order of magnitude stays the same if disk parameters are varied. This means that particles much larger than 1 cm should not be found transported as one piece to the outer parts of the disk or even the asteroid belt which is consistent with the largest parts in meteorites being cm-sized. Beyond 1 AU dust particles take longer than the available outburst time to rise and be blown away. Big particles will therefore only rise in the inner 1 AU.

For particles much smaller than 100 µm radiation pressure gets important (Saija et al. 2003; Krauss and Wurm 2004). This is added to the photophoretic force. In the case of FU Orionis disks the particles are lifted above the disk and are rapidly lost to the system as stellar radiation takes over. For both, radiation pressure and the star's gravity depend inversely on the square of the distance, the ratio between both forces always remains the same. If particles are illuminated by the central light source and if radiation pressure is stronger than gravity then these particles will continuously be accelerated away from the star and leave the system or travel as long as the outburst lasts. That way the region above the disk surface will be depleted in small individual particles. They will not be an obstacle to the transport of other particles like dust aggregates and CAIs.

While theoretical estimates on the strength of photophoresis are based on spherical particles, irregular particles of the size considered here will also experience a force away from the light source on the same order of magnitude, though the possible motions show more wealth in detail. This is currently under investigation.

During FU-Orionis events, CAIs can be transported efficiently to several AU distance due to photophoretic forces in specific corridors above the surface of the existing disk. Details depend on the illumination (opacity, luminosity) within the transport corridor, thermal conductivity, size, and morphology of the particles.

In any case, photophoresis close to the inner edge of the disk is strong enough to prevent infall of CAIs with any potential gas inflow. If the particles are embedded in an infall region with several tens of m/s inward velocity and if the light of the central source is attenuated by Rayleigh scattering of gas molecules or even dust, the particles will not move out far but stay bound to the inner region of 0.5 AU. Again, we note that photophoretic transport over the surface cannot provide transport to the asteroid belt in that case.

However, if the disk is flared and particles are propelled by photophoresis induced by full illumination then even in the case of strong accretion an outburst of 100 solar luminosities can transport particles into the asteroid belt.

Due to the number of parameters and uncertainties we did not elaborate on specific details here, but a sorting of particles with respect to their final position or rain out point according to their properties (size, thermal conductivity) is a likely outcome.

CONCLUSIONS

If the accretion is limited to the close vicinity of the star as e.g., suggested by Bell and Lin (1994) then particles can reach the asteroid belt even if we assume that extinction by gas is present but only if the outburst takes several thousand years. If we assume full illumination, particles can be transported to several tens of AU in only hundreds of years.

In all cases where outward transport is provided there is an inner region which is devoid of CAIs. As we cannot make thermal conductivities larger by any effect but only lower it and as lift is limited to sub-cm particles, even the weakest particles able to be transported will have final rain-out points distinct from their origin. To summarize, during FU-Orionis outbursts

- CAIs smaller than ~1 cm are able to counteract any strong inflow to the star and can move over the surface to several tenths of AU by photophoresis.
- CAIs larger than ~1 cm in size cannot be transported via surface drift as the (thermal) photophoretic lift is too small
- CAIs can move in certain corridors over the surface and be pushed to the asteroid belt in a few hundred years if radial opacity within the transport corridor is low.
- As part of low thermal conductivity aggregates, CAIs can be moved to the comet forming region beyond 10 AU on similar time scales.
- The efficient vertical photophoretic transport at the inner edge of the disk makes the transport mechanism more efficient for particles, such as CAIs, that formed close to the Sun, than for particles, such as chondrules that are believed to form further out.

The mechanism discussed only provides an outward flow but allows no further statements on the fate of the transported CAIs. It is tempting to assume that particles rain down to the midplane and stay there but we could only speculate why this is. The advantage of the transport over the surface is that—per definition—it occurs in a thin region. Particles will collide rarely with other particles. Only once they rain down to the midplane can collisions occur again with other particles. It is likely that the particles are rapidly built into larger bodies by collisional growth (Blum and Wurm 2008). This way they would not be transported back inward by other drifts but could maintain their radial distance to the star. CAIs that are freed from the bodies in later collisions again could then be assembled together with chondrules to the final chondrites. But, as noted, this is not a direct consequence of our transport mechanism. The problem of inward drift of small particles is an omnipresent problem in all disks and small particle models. Even in the case of turbulent mixing or outflow through the midplane (Ciesla 2007) the problems remain why we only see CAIs in a limited number of bodies and not evenly distributed throughout at least the asteroid belt.

If particles are locked up for a while in larger bodies, this would be an explanation but this requires that the bare particles reach their destination first. A surface flow, e.g., by photophoresis can provide this transport without interaction among particles. Transport in the midplane has to discuss collisional evolution already in the transport phase.

The mechanism discussed here is strongly influenced by the strength of the radiation reaching a particle and by a potential inflow/outflow. If the CAI corridor is not optically thin, e.g., if the surface of the disk is at larger scale heights and if the light source is obscured further out, the outward transport might stop way before the final accumulation points calculated above.

If our mechanism is responsible for transport of CAIs and if no midplane backward transport occurs we should not expect to see much evidence of CAIs in the terrestrial planets region. This is consistent with the lack of a ^{50}Ti anomaly which may be used to estimate the abundance of CAIs in the source material for differentiated asteroids and planets (Trinquier et al. 2007). The efficiency of the transport mechanism is more than sufficient to explain the inferred mass of transported CAIs in the early solar system. The process can transport CAIs that are up to cm-size but not larger which is in very good agreement with the maximum observed size of CAIs. Finally, the duration of the FU-Orionis events and thus the time window where transport is possible is consistent to the maximum inferred formation time interval for CAIs of 20 to 100 kyr (Itoh and Yurimoto 2003; Bizzarro et al. 2004, 2005).

Acknowledgments–G. Wurm is funded by the Deutsche Forschungsgemeinschaft. This research received support from the SYNTHESYS Project, which is financed by European Community Research Infrastructure Action under the FP6 “Structuring the European Research Area” Programme. The Center for Stars and Planets is funded by the Danish National Research Foundation and the University of Copenhagen’s Programme of Excellence. We thank Dr. Rubincam and two anonymous reviewers for very constructive reviews.

Editorial Handling—Dr. Christine Floss

REFERENCES

Alibert Y., Mordasini C., Benz W., and Winisdoerffer C. 2005. Models of giant planet formation with migration and disc evolution. *Astronomy & Astrophysics* 434:343–353.

Amelin Y., Krot A. N., Hutcheon I. D., and Ulyanov A. A. 2002. Lead isotopic ages of chondrules and calcium-aluminum-rich inclusions. *Science* 297:1678–1683.

Armitage P. J., Clarke C. J., and Palla F. 2003. Dispersion in the lifetime and accretion rate of T-Tauri discs. *Monthly Notices of the Royal Astronomical Society* 342:1139–1146.

Balbus S. A. and Hawley J. F. 1991. A powerful local shear instability in weakly magnetized disks. I—Linear analysis. II—Nonlinear evolution. *The Astrophysical Journal* 376:214–233.

Bell K. R. and Lin D. N. C. 1994. Using FU Orionis outbursts to constrain self-regulated protostellar disk models. *The Astrophysical Journal* 422:987–1004.

Beresnev S., Chernyak V., and Fomyagin G. 1993. Photophoresis of a spherical particle in a rarefied gas. *Physics of Fluids A: Fluid A5*:2043–2052.

Blum J. and Wurm G. 2008. The growth mechanism of macroscopic bodies in protoplanetary disks. *Annual Review of Astronomy and Astrophysics* 46: 21–56.

Bizzarro M., Baker J. A., and Haack H. 2004. Mg isotope evidence for contemporaneous formation of chondrules and refractory inclusions. *Nature* 431:275–278.

Bizzarro M., Baker J. A., and Haack H. 2005. Corrigendum: Mg isotope evidence for contemporaneous formation of chondrules and refractory inclusions. *Nature* 435, 1280.

Brauer F., Dullemond C. P., and Henning T. 2008. Coagulation fragmentation and radial motion of solid particles in protoplanetary disks. *Astronomy and Astrophysics* 480:859–877.

Brearley A. J. and Jones R. H. 1998. Chondritic meteorites. In *Planetary materials*, edited by Papike J. J. Reviews in Mineralogy and Geochemistry, vol. 36. Washington, D.C.: Mineralogical Society of America.

Bottke W. F. Durda D. D., Nesvorný D., Jedicke R., Morbidelli A., Vokrouhlický D., Levison H. F. 2005. Linking the collisional history of the main asteroid belt to its dynamical excitation and depletion. *Icarus* 179:63–94.

Ciesla F. J. 2007. Outward transport of high-temperature materials around the midplane of the solar nebula. *Science* 318:613–615.

Chiang E. I., Joung M. K., Creech-Eakman M. J., Qi C., Kessler J. E., Blake G. A., and van Dishoeck E. F. 2001. Spectral energy distributions of passive T-Tauri and Herbig Ae disks: Grain mineralogy, Parameter dependences, and comparison with infrared space observatory LWS Observations. *The Astrophysical Journal* 547:1077–1089.

Dalgarno A. and Williams D. A. 1962. Rayleigh scattering by molecular hydrogen. *The Astrophysical Journal* 136:690.

Hayashi C., Nakazawa K., and Nakagawa Y. 1985. in *Protostars and planets II*, edited by Black D. C., Matthews M. S. Tucson: The University of Arizona Press. pp. 1100–1153.

Hartmann L. and Kenyon S. J. 1996. The FU Orionis phenomenon. *Annual Review of Astronomy and Astrophysics* 34:207–240.

Herbig G. H. 1977. Eruptive phenomena in early stellar evolution. *The Astrophysical Journal* 217:693–715.

Herrmann F. and Krivov A. V. 2008. Effects of photophoresis on the evolution of transitional circumstellar disks. *Astronomy and Astrophysics* 476:829–839.

Hutchins D. K., Harper M. H., and Felder R. L. 1995. Slip correction measurements for solid spherical particles by modulated dynamic light scattering. *Aerosol Science and Technology* 22: 202–218.

Itoh S. and Yurimoto H. 2003. Contemporaneous formation of chondrules and refractory inclusions in the early solar system. *Nature* 423:728–731.

Johansen A., Brauer F., Dullemond C. Klahr, and H., Henning T. 2008. A coagulation-fragmentation model for the turbulent growth and destruction of preplanetesimals. *Astronomy and Astrophysics* 486:597–611.

Krauss O. and Wurm G. 2004. Radiation pressure forces on individual micron-size dust particles: A new experimental approach. *Journal of Quantitative Spectroscopy and Radiative Transfer* 89:179–189.

Krauss O. and Wurm G. 2005. Photophoresis and the pile-up of dust in young circumstellar disks. *The Astrophysical Journal* 630: 1088–1092.

Krauss O., Wurm G., Mousis O., Petit J.-M., Horner J., and Alibert Y. 2007. The photophoretic sweeping of dust in transient protoplanetary disks. *Astronomy & Astrophysics* 462:977–987.

Lachaume R. 2004. The vertical structure of T-Tauri accretion discs. IV. Self-irradiation of the disc in the FU-Orionis outburst phase. *Astronomy and Astrophysics* 422:171–176.

Liffman K. 2005. Chondrule and metal grain size sorting from jet flows. *Meteoritics & Planetary Science* 40:123–138.

Malbet F., Lachaume R., Berger J.-P., Colavita M. M., di Folco E., Eisner J. A., Lane B. F., Millan-Gabet R., Ségransan D., and Traub W. A. 2005. New insights on the AU-scale circumstellar structure of FU-Orionis. *Astronomy & Astrophysics* 437:627–636.

Mousis O., Petit J.-M., Wurm G., Krauss O., Alibert Y., and Horner J. Photophoresis as a source of hot minerals in comets. *Astronomy & Astrophysics* 466:L9–L12.

Presley M. A. and Christensen P. R. 1997. Thermal conductivity measurements of particulate materials 1. A review. *Journal of Geophysical Research* 102:6535–6549.

Reipurth B. 2003. FU Orionis eruptions and the formation of close binaries. In *Open issues in local star formation*, edited by Lépine J. and Gregorio-Hetem J. Kluwer Academic Publishers. pp. 269–278.

Rohatschek H. 1985. Direction, magnitude and causes of photophoretic forces. *Journal of Aerosol Science* 16:29–42.

Saija R., Iatì M. A., Giusto A., Borghese F., Denti P., Aiello S., and Cecchi-Pestellini C. 2003. Radiation pressure cross-sections of fluffy interstellar grains. *Monthly Notices of the Royal Astronomical Society* 341:1239–1245.

Scott E. R. D. and Krot A. N. 2006. Chondrites and their components. In *Meteorites, comets and planets.* Treatise on Geochemistry, vol. 1. Elsevier.

Shu F. H., Shang H., and Lee T. 1996. Toward an astrophysical theory of chondrites. *Science* 271:1545–1552.

Takeuchi T. and Lin D. N. C. 2002. Radial flow of dust particles in accretion disks. *The Astrophysical Journal* 581:1344–1355.

Takeuchi T. and Krauss O. 2008. Photophoretic structuring of circumstellar dust disks. *The Astrophysical Journal* 677:1309–1323.

Trinquier A., Bizzarro M., Ulfbeck D., Krot A., and Connelly J. N. 2007. Origin of titanium isotope heterogeneity in the protoplanetary disc. In *Workshop on Chronology of Meteorites and the Early Solar System.* Houston: Lunar and Planetary Institute.

Watanabe S. I. and Lin D. N. C. 2008. Thermal waves in irradiated protoplanetary disks. *The Astrophysical Journal* 672:1183–1195.

Wurm G. 2007. Light-induced disassembly of dusty bodies in inner protoplanetary discs: Implications for the formation of planets. *Monthly Notices of the Royal Astronomical Society* 380:683–690.

Wurm G. and Krauss O. 2006. Concentration and sorting of chondrules and CAIs in the late solar nebula. *Icarus* 180:487–495.

Wurm G., Krauss O., and Haack H. 2006. From size sorting of chondrules to accretion of parent bodies—The effects of photophoresis (abstract). *Meteoritics & Planetary Science* 41: A191.

Weidenschilling S. J. 1977. Aerodynamics of solid bodies in the solar nebula *Monthly Notices of the Royal Astronomical Society* 180: 57–70.

Weidenschilling S. J and Cuzzi J. N. 1993. In *Protostars and planets III*, edited by Levy E. H. and Lunine J. I. Tucson: The University of Arizona Press. 1031 p.

Zolensky M. E., Zega, Yano H., Wirick S., Westphal A. J., Weistberg M. K., Weber I., Warren J. L., Velbel M. A., Tsuchiyama A., Tsou P., Toppani A., Tomioka N., Tomeoka K., Teslich N., Taheri M., Susini J., Stroud R., Stephan T., Stadermann F. J., Snead C. J., Simon S. B., Simionovici A., See T. H., Robert F., Rietmeijer F. J. M., Rao W., Perronnet M. C., Papanastassiou D. A., Okudaira K., Ohsumi K., Onishi I., Nakamura-Messenger K., Nakamura T., Mostefaoui S., Mikouchi T., Meibom A., Matrajt G., Marcus M. A., Leroux H., Lemelle L., Le L., Lanzirotti A., Langenhorst F., Krot A. N., Keller L. P., Kearsley A. T., Joswiak D., Jacob D., Ishii H., Harvey R., Hagiya K., Grossman L., Grossman J. N., Graham G. A., Gounelle M., Gillet P., Genge M. J., Flynn G., Ferroir T., Fallon S., Ebel D. S., Zu R. D., Cordier P., Clark B., Chi M., Butterworth A. L., Brownlee D. E., Bridges J. C., Brennan S., Brearley A., Bradley J. P., Bleuet P., Bland P. A., and Bastien R. 2006. Mineralogy and petrology of comet 81P/Wild 2 nucleus samples. *Science* 314:1735–1739.