1. Introduction

The process of planetary formation is widely accepted to be initiated in circumstellar disks by the collisional coagulation of dust grains to larger objects (Henning et al. 2006; Natta et al. 2007). Evidence of grain growth to particle sizes beyond those typically observed in the interstellar medium is provided by mid-infrared spectroscopy of disks around young stars (Bouwman et al. 2001; van Boekel et al. 2003; Apai et al. 2004; Kessler-Silacci et al. 2007; Sicilia-Aguilar et al. 2007). Analyses of millimeter interferometry data of disks implies that large populations of dust grains exist with particle radii up to several millimeters (Testi et al. 2003; Wilner et al. 2005; Rodmann et al. 2006).

Models of dust particle growth in protoplanetary disks predict coagulation, which supports the idea of planetesimal formation by particle hit and stick mechanisms. Numerical calculations support the formation of cm-sized particles within a few $10^3$ orbital timescales in the inner parts of the disk (Weidenschilling 1980). After particles have grown to larger sizes, they can also be affected by other processes described by alternative planet formation scenarios. For example, large grains experience vertical settling, which involves the formation of a dense midplane dust layer (Garaud & Lin 2004). This layer can be affected by gravitational instability (Goldreich & Ward 1973; Weidenschilling 1979; Youdin & Shu 2002; Schräpler & Henning 2004; Garaud & Lin 2004) – an issue that is still highly debated. Due to the overwhelming amount of observational data for protoplanetary disks available, models of dust particle growth have attracted more attention (Tanaka et al. 2005; Dullemond & Dominik 2005; Nomura & Nakagawa 2006; D’Alessio et al. 2006; Ormel et al. 2007; Ciesla 2007). All of these particle evolution models can explain observational disk features such as, for example, the group I/II disk classification (Meeus et al. 2001; Dullemond & Dominik 2004) or the disappearance of infrared excess in the spectra of disks with ages higher than a few Myrs (Haisch et al. 2001; Carpenter et al. 2005), although, there are still many open observational riddles that these models will hopefully answer in the near future.

Models of protoplanetary disks do not only help to interpret observational data; they also identify the serious obstacles to planetesimal formation (Youdin 2004; Dominik et al. 2007). One of these obstacles is particle fragmentation. Due to the high particle relative velocities in disks that can reach 100 m/s (Weidenschilling 1977; Ormel & Cuzzi 2007), particle collisions lead to particle destruction instead of particle growth (Blum & Wurm 2000; Brauer et al. 2008; Johansen et al. 2008). Depending on the disk model, dust particle growth is inhibited significantly by high-speed impacts of particles around a meter size. Even for times as long as 1 Myr, solid particles are unable to overcome the fragmentation barrier and the formation of planetesimals as precursors for Earth-like or Jovian planets, therefore, poses a major problem. Despite this theoretically predicted inability for planetesimals to form, the orbital decay of dust particles can, nevertheless, reproduce the observed evolution in the spectral energy distribution (Haisch et al. 2001; Carpenter et al. 2005). The presence of a growth barrier is, therefore, not in contradiction with observations.

Several mechanisms in protoplanetary disks can produce planetesimal formation. Johansen et al. (2007) showed that the non-linear feedback of dust onto gas can lead to the rapid formation of gravitationally bound clumps of dust, which subsequently form Ceres-size bodies. The dust particles, however, must have already grown to some meters in size before this scenario can take place. Another possibility for solving the formation problem is particle trapping in gas pressure maxima.
The surface density along the snow line is described in detail in Kretke & Lin (2007). This particle retention mechanism requires the presence of an evaporation front, for example, the snow line, which acts in the following way. As we travel through the snow line in a direction away from the central star, the dust-to-gas ratio increases suddenly. This jump in dust density affects the strength of the magnetorotational turbulence, since the amount of free electrons in the disks strongly depends on the dust density. With increasing dust density, the amount of turbulence in the disk decreases (Sano et al. 2000; Ilgner & Nelson 2006). We assume a constant mass accretion rate throughout the disk. The gas surface density then has to be higher in local than in high disk turbulent regions for the gas mass accretion to remain at a similar value. The sudden increase in the dust density could therefore also reproduce a sudden increase in gas densities. For certain accretion rates, Kretke & Lin (2007) found the occurrence of a local gas density bump in which solid particles tend to accumulate. In their simulations, dust particle retention reproduced very high surface dust densities of the order of several $10^3$ g/cm$^2$, which again raises concern about gravitational instability.

However, even for a particle retention mechanism similar to that described above, the growth of solid material towards larger sizes remains an open issue. Gas pressure maxima may decrease relative radial particle velocities triggering coagulation; the most severe reason for violent particle fragmentation is not however radial drift but the turbulent nature of the protostellar disk itself. Relative turbulent particle velocities are approximately 10 m/s (Ormel & Cuzzi 2007; Völk et al. 1980) and particle sticking at these high speeds is extremely unlikely. Nevertheless, Ciesla (2007) found that particles can grow to several 10 m in radius if we consider layered MRI active disks. Under certain circumstances, MRI is only active in the upper layers of the disk, while the disk midplane is almost laminar. Since most of the larger grains are located around the midplane where the disk is quiescent, dust growth is not inhibited by the high-speed collisions that produce particle fragmentation.

We combine three ingredients for a planetesimal formation model. We consider dust particle growth, particle fragmentation and radial motion (Brauer et al. 2008) around the snow line (Kretke & Lin 2007) in a layered MRI active protoplanetary disk (Ciesla 2007). The inclusion of a snow line in our simulations provides a particle retention mechanism which almost erases the radial drift velocities favouring particle growth. We adopt a layered MRI-driven disk to circumvent particle fragmentation in the midplane of the disk due to turbulent motions of the gas. We investigate whether solid particles can overcome the fragmentation barrier and produce larger objects, which represent the possible precursors to the planets. We study the influence of two parameters, namely the gas accretion rate $M_\text{acc}$ and the critical threshold velocity for fragmentation $v_t$.

2. Model

We assume a background gas disk which is in a steady state and, hence, does not change with time. The calculation of the gas densities around the snow line are described in detail in Kretke & Lin (2007). We adopt all of the parameter values presented in that paper apart from the residual turbulence value around the midplane $\alpha_0$, which we set to be $10^{-5}$ corresponding to self-induced turbulence (Weidenschilling 1979; Weidenschilling & Cuzzi 1993). The water evaporation front, which is the important element in our model, is located at 3 AU (Lecar et al. 2006). The gas surface densities that we adopt in our simulations are shown in Fig. 1 for different gas accretion rates $M_\text{acc}$. The surface gas densities for different gas accretion rates which we will use in our simulations as calculated by Kretke & Lin (2007) and discussed in Sect. 2. The snow line is located at 3 AU.

![Fig. 1: The surface gas densities for different gas accretion rates without turbulent mixing.](image)

![Fig. 2: Maximum radial drift velocity $v_N$ for different gas accretion rates without turbulent mixing.](image)

For different accretion rates, this quantity is shown in Fig. 2 as a function of disk location. The equations for the gas pressure $P_g$ and the Kepler frequency $\Omega_k$ are given in Brauer et al. (2008). From this maximum radial drift velocity, we can calculate the actual radial drift speed of a particle of a certain size and solve the continuity equation in the radial direction for all dust particle species. Radial diffusion due to turbulent mixing is in addition included in the model.

Figure 2 shows, that for sufficiently small accretion rates, grain retention will occur around the snow line close to 3 AU inside the disk. For dust particle growth, it is even more important...
Henning 2004). We solve the sedimentation with a semi-analytical model, assuming that the particle distribution occurs. Apart from the accretion rate \( \dot{M}_{\text{acc}} \), the threshold fragmentation velocity is the second parameter that we consider. The accretion rate of a protoplanetary disk decreases with time. Therefore, Fig. 3 illustrates the advantage of our planetesimal formation mechanism at different stages of disk evolution. In the early stages, the gas surface densities are not significantly affected by the sharp decrease in dust-to-gas ratio at the snow line because the accretion rate is too high. Hence, we do not find that particles grow to become very large objects in this case. With decreasing accretion rate, the surface gas density becomes lower, and the gas pressure becomes higher, which leads to higher gas accretion rates. This implies that we must consider a different drag force regime, namely the Stokes regime instead of the Epstein regime. We implemented this regime into our model to account for the high gas densities (Weidenschilling 1977).

### 3. Results

Figure 3 shows the particle distribution after 1800 yrs of disk evolution for different accretion rates. In this simulation, we adopted a critical threshold fragmentation velocity of 10 m/s. This plot indicates that particles can grow to some \( 10^2 \) m in size around the ice evaporation front subject to the condition that the gas accretion rate is not too high. It also shows that fragmentation inhibits particle growth towards m-sized particles in other disk regions, for example around 4 AU. To unveil the importance of collective effects at the snow line, we estimate the dust-to-gas ratio in the midplane of the disk. The vertically integrated ratio in the case of \( M = 9 \times 10^{-3} M_{\odot} \) is of the order \( \epsilon_0 = 10/10^2 = 10^{-3} \), as inferred from Figs. 1 and 3. The dust-to-gas ratio in the midplane is then at least \( \epsilon_{\text{mid}} \approx \epsilon_0 \sqrt{1/\alpha} \approx 10^{-3} \sqrt{10^3/10^3} = 10 > 1 \), which means that collective effects play a non-negligible role. Since collective effects strongly influence the radial drift behaviour of the dust, further investigation of this issue is certainly required.

The accretion rate of a protoplanetary disk decreases with time. Therefore, Fig. 3 illustrates the advantage of our planetesimal formation mechanism at different stages of disk evolution. In the early stages, the gas surface densities are not significantly affected by the sharp decrease in dust-to-gas ratio at the snow line because the accretion rate is too high. Hence, we do not find that particles grow to become very large objects in this case. With decreasing accretion rate, the surface gas density becomes lower, and the gas pressure becomes higher, which leads to higher gas accretion rates. This implies that we must consider a different drag force regime, namely the Stokes regime instead of the Epstein regime. We implemented this regime into our model to account for the high gas densities (Weidenschilling 1977).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3.pdf}
\caption{The particle distribution after 1800 yrs of disk evolution as discussed in Sect. 3. Shown is a contour plot of the surface dust density as a function of disk location and particle radius for four different accretion rates. The figure indicates that particles break through the fragmentation barrier if the accretion rate is not too high. The critical fragmentation velocity is 10 m/s in this simulation.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4.pdf}
\caption{As Fig. 3, but now for four different critical threshold fragmentation velocities. The figure indicates that dust particles can break through the fragmentation barrier if the threshold fragmentation velocity is at least 5 m/s. In this simulation, we adopted an accretion rate of \( \dot{M}_{\text{acc}} = 8 \times 10^{-3} M_{\odot}/\text{yr} \).}
\end{figure}
more and more affected by the snow line producing the forma-
tion of large boulders as shown in Fig. 3. At this stage of disk
evolution, planetesimal formation could occur. At later stages,
the surface gas densities will have declined towards a level at
which the entire disk becomes MRI active and the mechanism is
unable to operate. 

The dust particle distribution after 1800 yrs, but now
for different critical fragmentation velocities, is shown in
Fig. 4. In this calculation, we considered an accretion rate
M_{acc} = 8 \times 10^{-9} M_{sun}/yr. This plot indicates that dust parti-
cles can overcome the fragmentation barrier and grow to nearly
km-size if the critical threshold velocity is at least 5 m/s. For
the case \upsilon_1 = 1 m/s, we do not find particles that are able to grow
to larger than a meter in radius. This is due to the fact that relative
turbulent velocities in our quiescent midplane are still of the or-
ginal size.

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