Dust Evolution in Protostellar Accretion Disks

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We calculated the collapse of a $\rho \propto r^{-2}$ density peaked, slowly rotating molecular cloud core by 2D numerical radiation hydrodynamical simulations. The dynamics of the dust grains is calculated applying a multicomponent fluid model. Acceleration by the radiation field, coupling to the gas component by dynamical friction, coagulation and shattering of the grains is included. Relative velocities between the dust particles are caused by differential radiative acceleration, differential sedimentation into the equatorial plane of the accretion disk, turbulence and Brownian motion.

Dust coagulation leads to significant modifications of the dust size distribution during the collapse of a molecular cloud core and the formation of a protostellar accretion disk. Small grains $\lesssim 0.1\,\mu$m are removed from the mass spectrum quickly and efficiently in the midplane of the disk. When compact spherical dust grains are assumed, large grains with sizes of several $10\,\mu$m are produced by coagulation during collapse phases. The accretion shock front leads to relative velocities of $\approx$ 1 km s^{-1} between the dust grains because of size dependent braking. Within the accretion shock and relaxation zone strong deviations from the MRN-distribution are caused by grain segregation. Large (μm sized) grains are able to pass through the shock without significant deceleration, whereas smaller grains slow down.

1. Compact Grains

As a first approximation we treated the grains as compact spheres. Their opacities are determined by Mie-theory and the interaction between gas and dust and between the grains themselves can be calculated in a straightforward manner. The dust evolution is traced at each (r, z) point by sampling the size distribution from 5 nm to 0.2 mm with 30 mass bins. Under the assumption that all grains have the same specific weight $\rho_s \approx 3$ g cm^{-3} the total mass range covers about fourteen orders of magnitude. Initially, only the first 20 mass bins were filled with an MRN distribution. Subsequent grain-grain collisions below a critical velocity $v_{\rm stick}$ resulted in coagulation to a grain with the sum of the colliding masses. At higher collision velocities but below $v_{\rm shatter}$ the grains were assumed to bounce off one another. For collision velocities larger than $v_{\rm shatter}$ the colliding constituents were broken apart and redistributed into the smaller mass bins. Values for $v_{\rm stick}$ and $v_{\rm shatter}$ were taken from the literature (see Suttner, Yorke & Lin 1999, ApJ 525, in press, for details and references). In Figs. 1 & 2 we show the results for $v_{\rm stick} = 10^3$ cm s^{-1} (ice-coated silicates) and $v_{\rm shatter} = 2.7$ km s^{-1}.

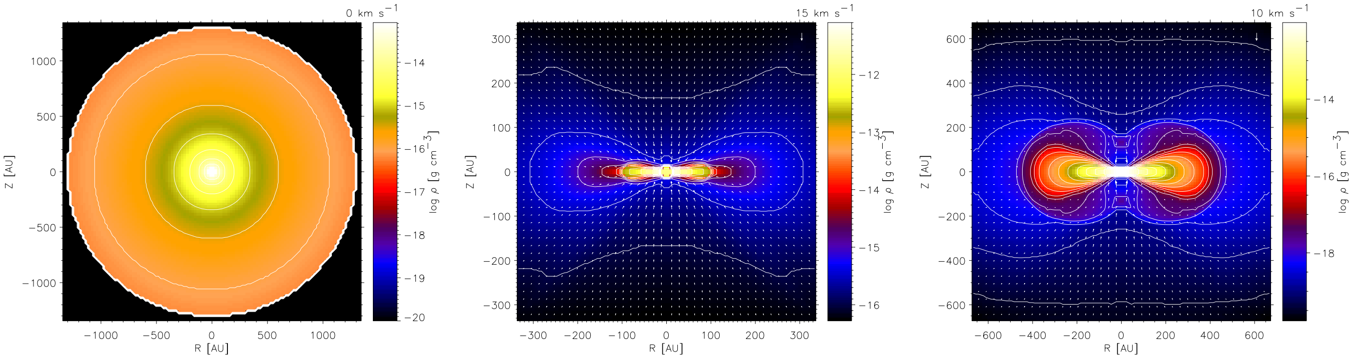

Figure 1: Density and velocity of the gas component for selected times $t = 0$, 5100 & 11 400 yr during the formation of the accretion disk.

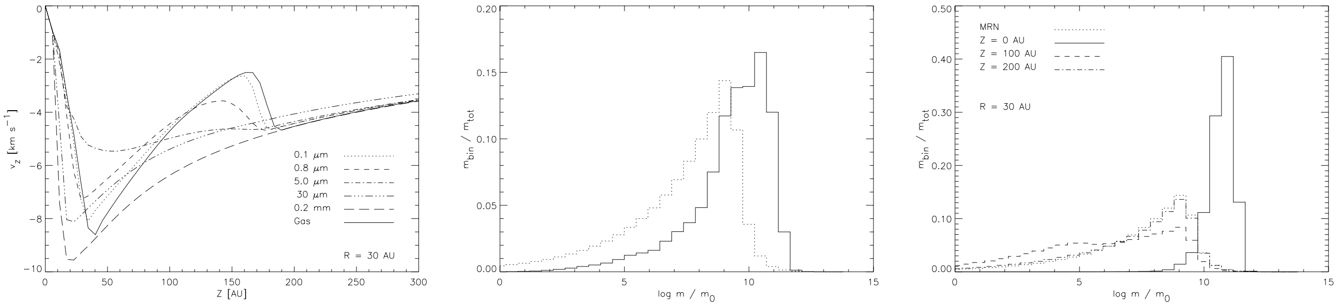

Figure 2: Grain parameters at $t = 11\,400$ yr. *left*: Vertical velocities v_z of selected grains through the accretion shock at $r = 30$ AU. *middle*: Evolved total mass spectrum (solid) and initial MRN-distribution (dotted). *right*: Grain mass spectrum at selected positions for $r = 30$ AU.

Fractal Grains

Dust in star forming regions is assumed to consist of rather fluffy coagulates. There are two extreme growing modes which determine the final structure of the grains: BPCA (ballistic particle-cluster aggregation) and BCCA (ballistic cluster-cluster aggregation). In our simulations we investigate both grain models. The dynamical behavior of these fractals is calculated following the approach of Ossenkopf (1993, A&A 280, 617) which gives analytic expressions for the specific gas-dust interaction cross sections of these fractal particles. This relation determines the coupling strength between gas and dust. The opacities are also calculated using a dust model which accounts for fractal grains (Henning and Stognienko 1996, A&A 311, 291). The parameters $v_{\rm stick}$ and $v_{\rm shatter}$ are adjusted accordingly (see Suttner et al. 1999). With the same initial conditions as for the compact grains we simulated the collapse of a protostellar cloud core. Fig. 3 shows the final stage of the numerical calculation and some properties of the fractal BCCA-grains.

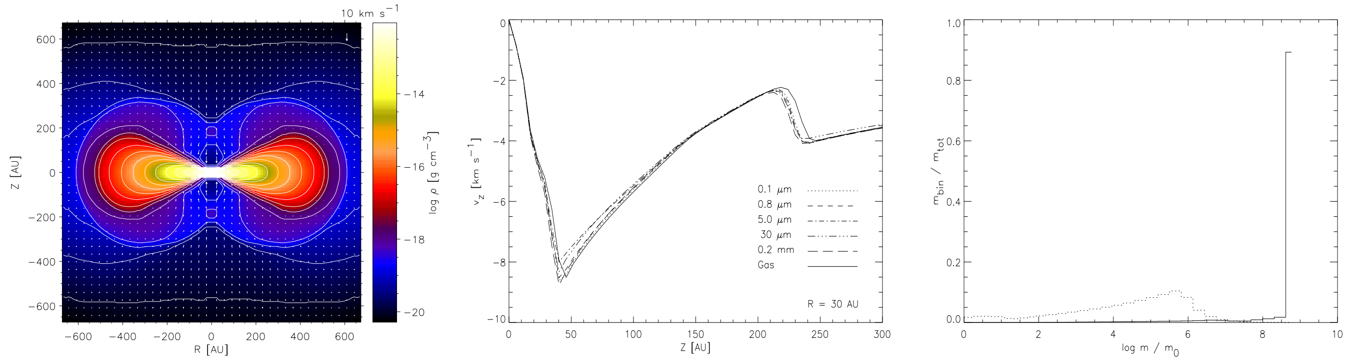

Figure 3: Evolution assuming BCCA-grains. *left*: Density and velocity of the gas component at $t = 12\,600$ yr. *middle*: Vertical velocity structure v_z of selected grain components at $r = 30$ AU. Note that fractal grains are more strongly coupled to the gas than the corresponding compact grains (Fig. 2). *right*: Grain size distribution at $(r, z) = (30, 0)$ AU compared to the initial MRN (dotted line) distribution. Almost all grains evolve into the largest bin considered within a short evolutionary time.

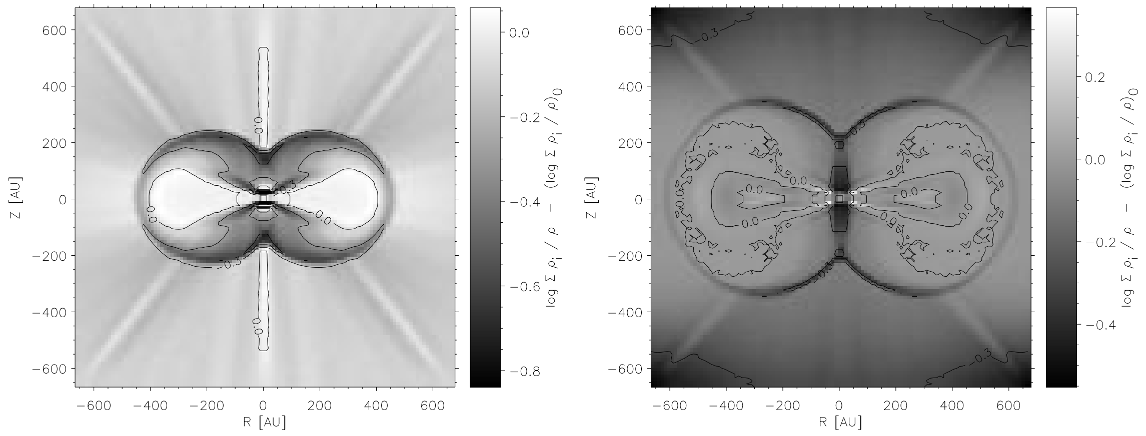

Figure 4: Dust to gas mass ratios for the two density/velocity structures displayed. *left*: Compact grains, $t = 11\,400$ yr. *right*: Fractal grains, $t = 12\,600$ yr.

Conclusions

- Coagulation is an important process during the formation of an accretion disk. Time scales as short as 10^3 yr are sufficient to modify the initial dust size distribution.
- During the collapse phase compact spherical grains do not grow beyond several 10 μm. Here the limiting sticking velocity plays a key role. BCCA–grains can build up to at least several 0.1 mm.
- Grain coagulation leads to modifications of the optical properties of the dust. The local opacity can be lowered by almost two orders of magnitude; the slope of the wavelength dependent absorption at submillimeter wavelengths as inferred from the SED is modified only slightly, however.