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Erosion of large aggregates in protoplanetary disks as a source of micrometer-sized particles

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Abstract

Observed protoplanetary disks consist of a large amount of micrometer-sized particles. Dullemond & Dominik [1] pointed out for the first time the difficulty in explaining the strong mid-IR excess of classical T-Tauri stars without any dust-retention mechanisms. Because high relative velocities in between micrometer-sized and macroscopic particles exist in protoplanetary disks, we present experimental results on the erosion of macroscopic agglomerates consisting of micrometer-sized spherical particles via the impact of micrometer-sized particles. We find that after an initial phase, in which an impacting particle erodes up to 10 particles of an agglomerate, the impacting particles compress the agglomerate's surface, which partly passivates the agglomerates against erosion. Due to this effect the erosion halts within our error bars for impact velocities up to $\sim$30 m s^{-1} [4]. For larger velocities, the erosion is reduced by an order of magnitude. This outcome is explained and confirmed by a numerical model. In a next step we build an analytical disk model and implement the experimentally found erosive effect. The model shows that erosion is a strong source of micrometer-sized particles in a protoplanetary disk. Finally we use the stationary solution of this model to explain the amount of micrometer-sized particles in observational infrared data of [2].

1 Experimental

1.1 Approach

To simulate the projectile-target collisions hypothesized for the protoplanetary disk, a jet of fast projectiles is directed to centimeter-sized targets in a vacuum environment. The mass loss or gain of the targets is determined by precision-weighing of the targets before and after exposure to a well-determined flux of projectiles. The experimental apparatus consists of a dust-dispersion cogwheel, a velocity filter and a vacuum chamber, which contains the target.

1.2 Results

We found that, after an initial stage in which an impacting particle can erode up to 10 dust grains from the fluffy dust agglomerate, the agglomerate is surface-compacted and passivated against further erosion at velocities lower than 26 ms^{-1}. At larger velocities, the erosion is reduced to 10% of its initial strength (see Fig. 1). We explained and confirmed the occurrence of impact-induced erosion with a numerical model, which is given as a solid line in Fig. 1.

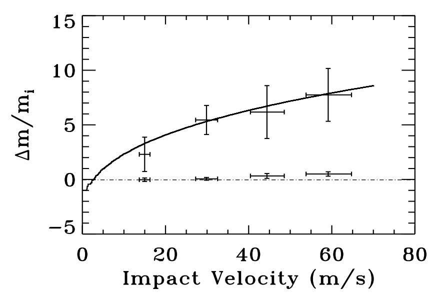

Figure 1: Erosion efficiency of target agglomerates. The upper data points with error bars were recorded at the onset of the experiment, in which the target agglomerate was very porous and not yet passivated, whereas the lower data points with error bars show a reduced erosion efficiency after the target-agglomerate's surface was almost passivated against erosion. The velocity error bars denote the velocity distribution stemming from the velocity filter. The vertical error bars denote one standard deviation of several measurements with different target agglomerates. The solid curve follows is the result of a numerical impact model.

2 Application to a Protoplanetary Disk

We developed an analytical disk model and implemented the experimentally found erosive effect. This model shows that erosion is a strong source of micrometer-sized dust particles in protoplanetary disks. The steady-state solution of the model shows that the micrometer-sized dust particles encompass a fraction of 0.20% (for α 10^{-2}) of the total dust mass in a disk if we assume that 70% of the disk mass is in the form of meter-sized dust aggregates with a filling factor of 40%. A further outcome of our model is that larger dust aggregates get eroded very fast at small Kepler radii, because they possess higher relative velocities to micrometer-sized particles see Fig. 2. Finally, we used our analytical model to discuss the amount of micrometer-sized particles in the observational data of [2]. We can reproduce their outcome with our erosion model.

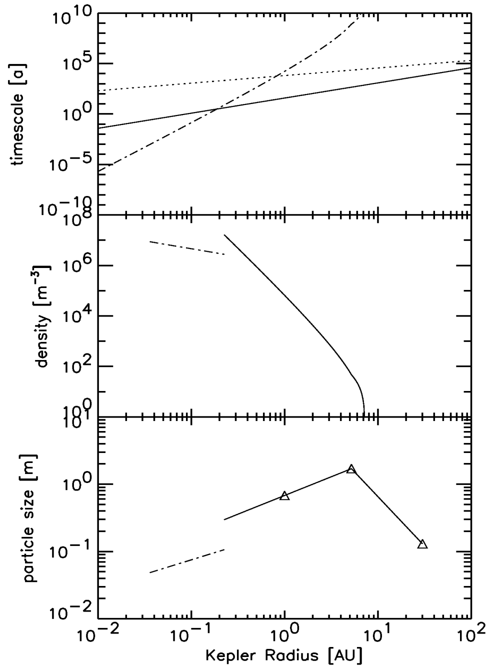

Figure 2: Protoplanetary disk with $\alpha = 10^{-2}$. Top graph: coagulation timescale (solid line), erosional timescale (dashed-dotted line), radial turbulent transport (dotted line). Center graph: number density of micrometer-sized particles at erosion timescale larger than the coagulation timescale (solid line), number density of micrometer-sized particles at erosion timescale smaller than the coagulation timescale (dashed-dotted line). Bottom graph: Particle size in which 70% of the total solid disk mass is contained (also maximum particle size) for erosion timescales larger than the coagulation timescale taken from [3] (triangles) and their power-law interpolation (solid line). Maximum particle size for erosion timescales smaller than the coagulation timescale (dashed-dotted line).

Acknowledgements

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