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ON THE IMPORTANCE OF EOLIAN EROSION FOR THE FORMATION OF PLANETS

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Summary
We discuss the possibility of erosion of dusty bodies in protoplanetary disks by a subsonic laminar gas flow. Our analysis is based on wind tunnel experiments on cm-size dust targets in an air gas flow of 63m/s at static gas pressures between 0.1mbar and 4.5mbar. We compare the results to numerical calculations of gas flow through porous bodies and the resulting drag force on dust aggregates at the surface. Our studies imply that a dusty body is efficiently eroded if the dynamic gas pressure of the surface flow exceeds gravity and/or cohesion. Applied to protoplanetary disks we find that objects on circular orbits might be relatively safe against erosion in a laminar gas flow even in a dense disk. However, if a body is stirred up to eccentric orbits its relative motion to the gas increases. Such objects can significantly be eroded if they consist of dust. As an extreme a 100m body with the rather low eccentricity of an Earth orbit might be eroded in a single orbit. The effect leads to a bias for planetesimals in low eccentricity orbits as objects with large eccentricities are destroyed more easily. Erosion of bodies in high eccentricity orbits and reaccretion of the dust aggregates by low eccentricity planetesimals might provide a special growth mode of planetesimals and protoplanets.

Introduction

It is widely accepted that planet formation takes place in protoplanetary disks and the building blocks of the planets are km-sized porous dusty bodies, so-called planetesimals. The planetesimals move in laminar disks on more or less circular orbits. They move faster than gas in the disk and experience a headwind, which reach velocities of approximately 60m/s [1][2]. Wurm et al. [3][4][5] showed that the gas drag and the head winds play an important and constructive part for the growth of planetesimals. On the other hand, if the gas flow is strong enough, it might be asked if gas drag could also destroy larger objects. If a dusty body moves through the gas, the gas imposes a shear force on the top layers of the dust. If this force is larger than the cohesive force (and gravity) particles will be removed and the body loses mass. The possibility of gas erosion is even more likely, if eccentric orbits for the planetesimals are considered. Hood [6] showed that close encounters with larger protoplanets can stir the large dusty bodies up to eccentric orbits. As soon as the orbits slightly deviate from circular orbits, the relative velocities between the planetesimals and the gas strongly increase. To be more quantitative we studied the interaction between gas flow and dusty bodies in protoplanetary disks in more detail. We carried out a series of wind tunnel experiments and numerical calculations which we report on here.

Experimental setup

A sketch of the experimental setup is shown in Fig. 1. The experiments are conducted in a circular closed wind tunnel with a pipe diameter of 32cm. The overall height is about 2m, the width is ~1.5m. The gas flow is generated by a roots pump. This provides high flow rates at low pressure. The pressure within the wind tunnel can be adjusted from about 10^{-3}mbar to 10mbar. The flow rate of the pump is adjustable. In the application described here we used a fixed flow rate of $3.14 m^3/s$ or a gas speed averaged over the cross section of 39m/s.

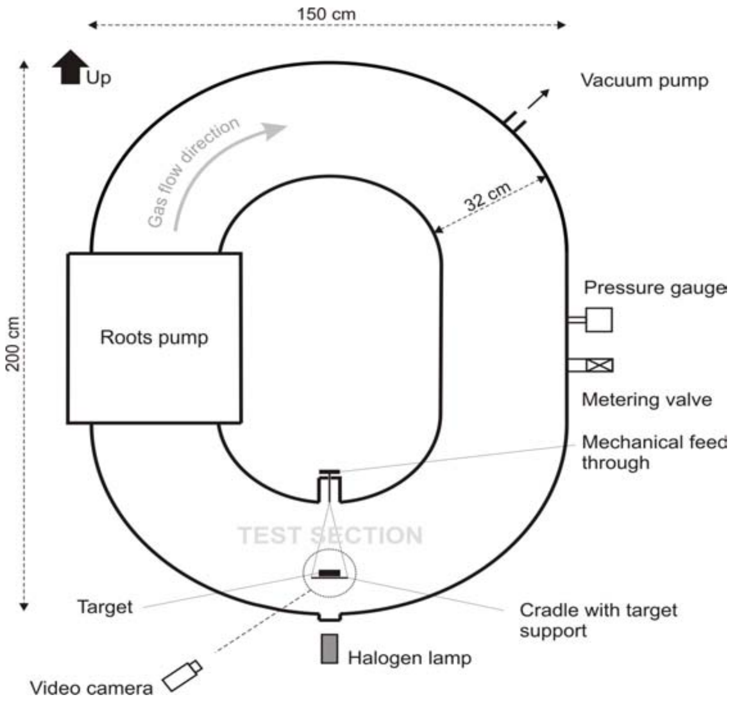

Fig. 1 Sketch of the experimental setup (side view). A dust target is placed in a string cradle in the test section of the wind tunnel. The cradle is adjusted in height by a mechanical feed through.

Gas flow parameters

The gas flow is not homogeneously distributed throughout the cross section. To quantify the spatial distribution of the gas flow we measured the velocity profile across the center of the wind tunnel in the test section in vertical direction.

The mean gas velocity obtained from the measured velocity profile is 39.5m/s (±2.0). The measurements show that the maximum gas velocity (63m/s) is located below the tunnel center, where it is almost constant over a height of several cm. The targets were placed inside this zone of constant gas velocity. We regard the results as equivalent to a target in an unbound system with a wind speed at infinity of 63m/s.

It is an important difference whether the gas flow is laminar or turbulent. Turbulent flow might lead to locally varying drag forces on particles, which might remove dust from the surface of a body differently from a laminar flow. Fully developed turbulence flow in tubes occurs at a Reynolds number of approximately Re ~ 10.000. In our experiments we varied the pressure in the range between 0.1 to 4.5mbar and the highest Reynolds numbers were Re = 3645. This is still far from being a fully developed turbulent flow. Therefore we regard the gas flow around our target to be close to the laminar conditions and our experiments as a good analog to a small body moving in a laminar protoplanetary disk.

Dust targets

As dust sample we chose a commercial SiO_2 powder with which we have used before in impact experiments [7][8]. Particle sizes were between 0.1 and 10μm. The targets were prepared by manually sieving the dust through a mesh with approximately 500μm openings. Thus, the targets consisted of individual, rather compact dust granules which were up to 500μm in size and sticked loosely together by cohesion forces.

Two target shapes were used during the experiments: piles with ~ 50mm base diameter and ~ 15mm height (Fig. 2a), and cuboids with a base of ~ 30mm x 50mm and heights of 12mm (Fig. 2b). Both target types had rough granular surfaces. Their average porosity was about 84% (± 2%) [7]. The piles were placed on a plastic half sphere and the cuboids on a metallic plate.

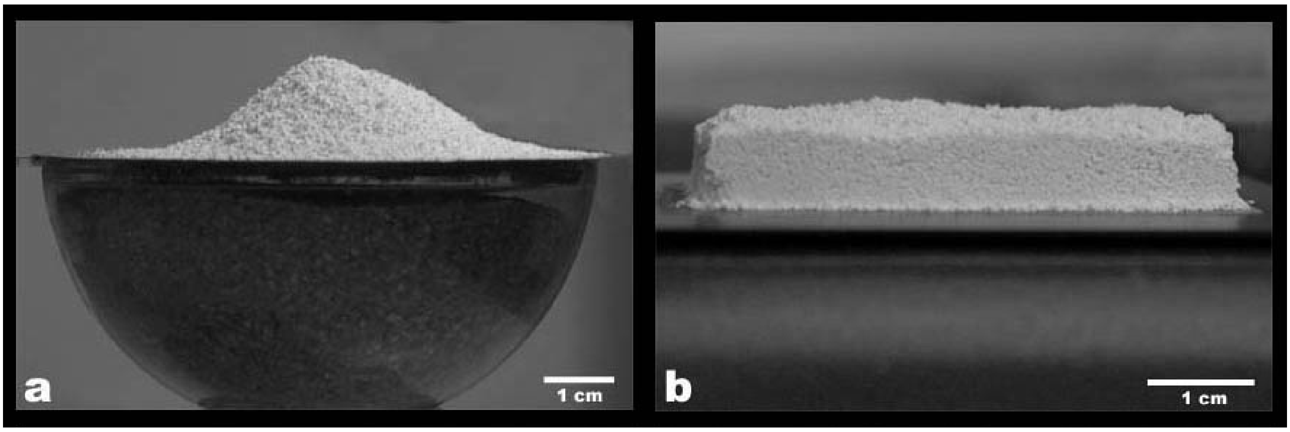

Fig. 2 Dust aggregates (targets). a: Dust pile b: Dust cuboid. For various experiments we used cuboids with 6, 9, or 12mm height.

Experiments description

Two base parameters were measured during the experiments: the erosion threshold and the erosion rate. We define erosion threshold as the gas pressure at which, at a default wind speed, the gas drag is strong enough to continuously remove dust granules from the target. With erosion rate we denote the dust mass eroded from the target in a certain time, at a given gas pressure (and at constant gas speed). All experiments were carried out with air at room temperature.

In the first series of experiments we detected at which minimum pressure dust is picked up by the gas flow. A target was placed in the wind tunnel and the tunnel was evacuated to about 10^{-2}mbar pressure. The roots pump was started and the wind speed adjusted to ~63m/s (39m/s average gas flow). The air pressure was gradually increased until dust motion from the target was observed.

The erosion rate was measured as follows: Before we placed the target in the wind tunnel, we determined its mass. The tunnel was evacuated and the roots pump was started. We kept the pump running for a certain time (60min in most experiments) at a given pressure. After that the wind tunnel was slowly filled with air again. The target was removed and weighed a second time.

Results

We measured the **erosion threshold** only for the pile-type targets (Fig. 2a). Initially, individual granules got entrained in the gas flow at a pressure of p_{stat}≈0.4mbar, but the number of particles strongly decreased with time. Also, a number of particles only moved down the pile without really being entrained in the gas flow. Particles that get entrained in the gas flow are lifted from different positions on the pile surface. As the pressure was further increased, more granules were lifted.

The **erosion rate** was measured for pile- and cuboid-type targets (Fig. 3). We carried out approximately ~40 experiments with both types. In the experiments with pile-type targets we varied the pressure between 0.3mbar and 4mbar, whereas the cuboids are used only for the pressure range between 2mbar and 4mbar. In the most experiments the targets are leaved for 60min in the gas flow.

At the beginning up to 0.7mbar the initial erosion rates, as can be seen from Fig. 4, are within the limits of the measurements and do not show a significant mass loss with time. Above ~0.7mbar the amount eroded increases to a measurable level but does not change systematically up to 1.4mbar. The mass loss was between 20mg/h and 50mg/h and the erosion rate do not show dependence on the increasing gas pressure. The piles do not change their shape.

With pressure increase above 2mbar the erosion changes its functional behaviour. At about 2mbar a strong increase in erosion rate occurs as seen in Fig. 5. The erosion rates for the dust piles are certainly well approximated by an exponential increase with pressure, whereas the cuboids results would equally well fit other laws.

Gas flow numerical calculations

To quantify the gas flow at the surface of our targets we carried out numerical calculations in 2d, using a commercial software package [9]. Our model consists of a tube section and the target. The tube section corresponds to the test section in our labor experiments. The target is placed in the center of the tube.

The numerical calculation in Fig. 3 shows the gas flow around a cuboid-type target. At the predefined conditions, 2mbar static gas pressure and 63m/s initial gas velocity, the calculation results in a clearly laminar flow around the target. The calculations show that the maximum velocity of v=44m/s is reached on the top front edge of the cuboids.

Calculations for a pile-type target at the same conditions show similar results. The flow around the pile is laminar and the highest velocity at the target surface is reached at the top of the pile.

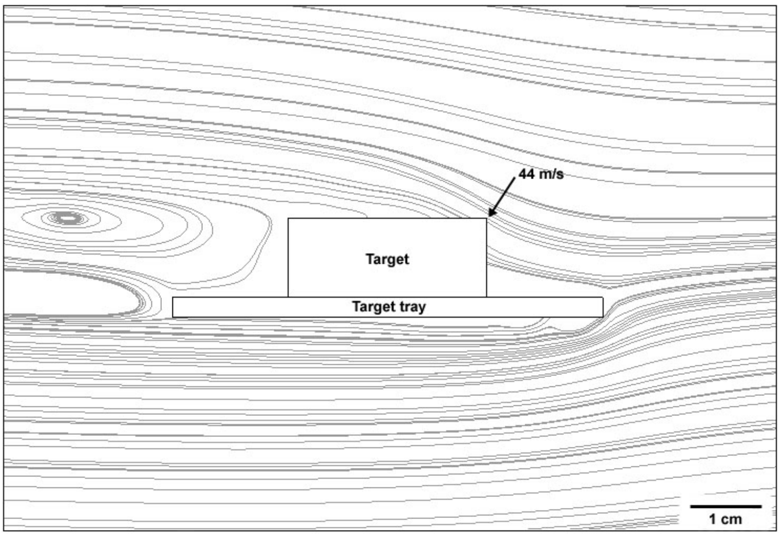

Fig. 3 Numerical calculation of the flow around a dust cuboid (streamline plot). On the plot is shown a cross-section through the target and the supporting plate. The arrow marks the streamline with maximal gas velocity.

Discussion of the results

In contrast to the numerical calculations, the first particles moving in the experiments are not necessarily originating at the top of pile. Some particles that get entrained in the gas flow are lifted from there but there are other particles that only roll down the pile from different positions on the surface. Several experiments on pile-type targets prepared the same way each time show that these motions start at a static pressure of p_{stat}≈0.4mbar. We simulated the gas flow around the pile at this pressure. According to the simulations the gas flow speed at the top of the target was v=13.5m/s. If we assume that the topmost particles would be within a free gas stream of velocity v we can calculate the gas force on a particle. For a dust granule of 500 µm in diameter the resulting force is $F_{gas} = 6 \cdot 10^{-8}$ N.

The individual granules in our targets have only a restricted number of contacts to other granules. If we neglect the cohesion, granules will continuously be picked up by the gas flow if the wind force can compensate gravity, which for the granules used is $F_g = 5 \cdot 10^{-7}$ N. This is larger than the gas drag force. Obviously the dust granules removed first are not typical dust granules, but rather individuals that are either smaller or more porous than the average, or both. Thus we can not regard the static pressure p_{stat}≈0.4mbar as real erosion threshold. This is also in agreement with the fact that the erosion rate does not show significant erosion below 2mbar as seen in Fig. 4.

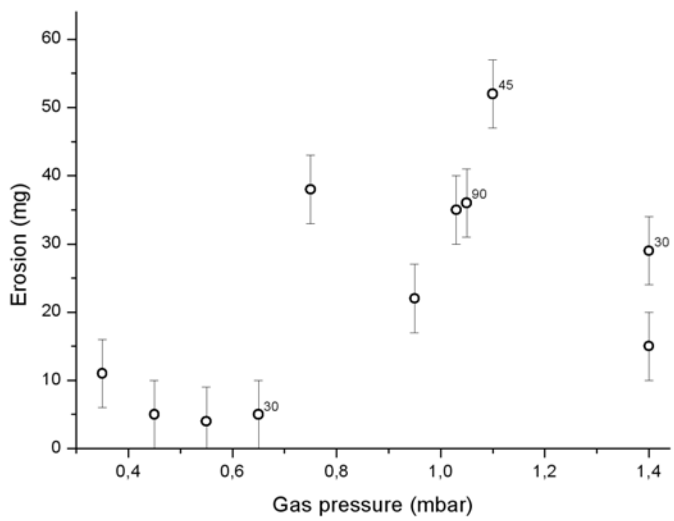

Fig. 4 Erosion of dust piles measured for static pressures up to 1.4mbar. Each measurement represents a new target. Most targets were placed in the gas flow for 60min. Except for a few targets that were measured for different times as indicated.

The erosion rate at pressures between 0.7mbar and 1.4mbar fluctuates strong, but we can not find a clear tendency for erosion increase. A strong increase of the erosion rate occurs first at about 2mbar. Obviously, up to this pressure there is still a selection of particles removed, which are more susceptible to gas drag than the majority of the dust. Thus, we regard the erosion threshold for dust pile targets to be reached at about 2mbar. Numerical calculations of the gas flow through the pile at 2mbar show that at this pressure the gas velocity at the top of the pile is 25m/s, which corresponds to a gas drag force of $F_{gas} = 1 \cdot 10^{-7}$ N. This is still somewhat smaller than the gravitational force. We have to consider that the numerical calculations are only a 2d approximation. A 3d treatment would increase the velocity at the top of the pile.

Above 2mbar the erosion rates for the dust piles increase exponential with pressure. Obviously the gas drag at these pressures is strong enough to erode all particles on the target surface, regardless their size.

The erosion for cuboid-type targets above 2mbar show similar behaviour as for the piles. The erosion rate increases strong with the pressure (Fig. 5). The gas drag force at the target surface at 2mbar is $F_{gas} = 3\cdot10^{-7}$ N.

In view of the experiments and numerical calculations we find the following:

Erosion threshold: *The experiments and calculations suggest that erosion of a dusty surface of a porous body in a laminar gas flow occurs as soon as the gas drag on a surface particle is stronger than the forces keeping the particle attached to its inner neighbours either gravity or cohesion. If a dusty body is 1dm in size, consists of compact dust aggregates of about 0.5mm in size, and moves through air at about 63m/s it starts to get eroded at 2mbar.*

Erosion rate: *Erosion of a cuboid takes place at the front edges. It depends linearly on size as long as the gas flows are similar. If a dusty body is 1dm in size, consists of compact dust aggregates of about 0.5mm in size and moves through air at about 63m/s the erosion rate at the erosion threshold of 2mbar is about 100mg/h.*

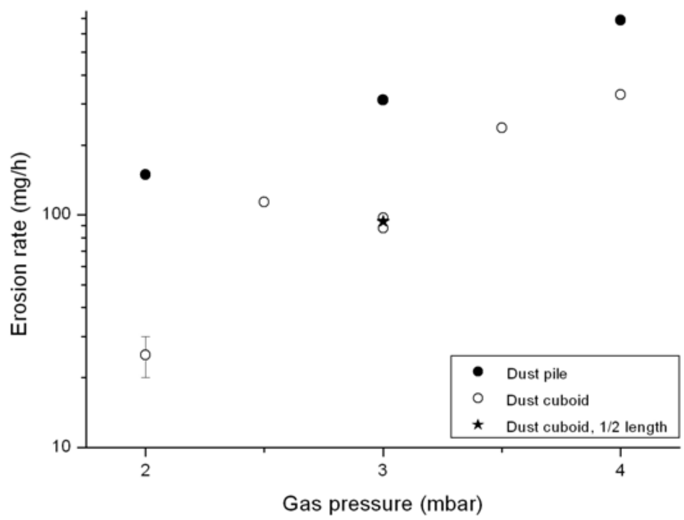

Fig. 5 Erosion rate over gas pressure for piles and cuboids. Filled circles are for piles. Open circles are for cuboids with the short side facing the gas flow. The star symbol at 3mbar marks a cuboid target with half the length (not discussed here).

Application to protoplanetary disks

Our results can immediately be applied to small bodies in protoplanetary disks moving on circular orbits. Our experimental settings were chosen to match the real conditions in these disks. Erosion in our experiments occurred at 2mbar. Since the protoplanetary disks consist mostly of hydrogen, the dynamic pressure is a factor 12.4 smaller compared to our experiments in air. Erosion in the disks would occur at 25mbar. This is on the edge of even the most massive disk models [10][11]. Small bodies might lose particles under the most extreme conditions close to the star inside of Mercury's orbit but typically they are safe against erosion.

Relative velocities between a solid (dusty) body and the gas strongly increase as soon as the orbits slightly deviate from circular orbits. An eccentricity of only 1-2% would result in 100 times increase in dynamic pressure. This mean that a body on a slight eccentric orbit will feel a 100 times stronger headwind. The gas drag would be enough to erode the body.

A crude estimate of possible mass loss would be as follows: We consider a cube shaped planetesimal and the mass loss occurring at the edges, thus being proportional to 4 times its length. We further assume that the side of the planetesimal is 1km long and moves with about 600m/s through the gas at 1mbar. If we extrapolate our results and assume similar values apply for km-size bodies this is about 1kg/hm mass loss or 4000kg/h for our 1km body. On an Earth orbit which assumes a rather dense disk model, this is $35x10^6$ kg per orbit, which is 3.5 % of the mass of the km dust cube (density 1g/cm). Since we assume erosion to be linear with size but as the total mass varies with the third power, smaller bodies are eroded more efficiently. E.g. a 100m size body at otherwise same parameters is eroded within a single orbit.

We note that this is only a very rough estimate. Erosion rates for large bodies might not be scaled 1:1 from our experiments. It also has to be considered that dusty bodies might be more cohesive. If cohesion is stronger at the surface, only weak parts get eroded. This might lead to a selection effect where more cohesive dusty bodies survive best.

Conclusion

Erosion by gas flow is an important mechanism for loosely built dusty planetesimals. The eolian erosion provides an effective mechanism to recycle material and takes an active part in planet formation. Thereby it leads to the preferential survival of larger bodies on orbits with no or only small eccentricities, at least in the inner part of the early Solar System.

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