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# PLANET FORMATION IN HIGH VELOCITY IMPACTS

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***Abstract***

*We discuss the problem of planet formation and give an account of the standard model. Our aim is to investigate some missing links in this model. In impact experiments we study central collisions between mm-sized dust projectiles and cm-sized dust targets. Collision velocities range from 6 to 38 m/s. The general outcome of a collision strongly depends on the target type. We prepared highly porous targets (porosity between 74% and 84%) and compressed targets with porosity of 68%. Impacts into porous targets result in craters, which are several mm deep and 2-3 cm in diameter. We observe ejecta that originate not from the crater but from the whole target surface. Responsible for particle ejection are elastic waves induced by the impact. Most of the mass of the projectile is added to the target mass due to gravity but mass loss of the target would result under microgravity. Impacts into compressed targets result in a pyramid like dust structure on top of the original target surface. At collision velocities up to 25 m/s approximately 50% of the mass of the projectile rigidly sticks to the target after the collision. For collisions below 13 m/s rebound and a small degree of fragmentation occur. Here, net growth of a body is possible in high speed collisions. This supports the idea that planetesimal formation via collisional growth is a viable mechanism at higher impact velocities.*

## *1. Introduction*

The problem of planet formation is one of the most fundamental problems of science, and is one of the most active fields of research in astronomy, astrophysics, and planetology. In the last decade we have received a lot of new information not only about our Solar System, but also about other stellar systems harboring extrasolar planets. Only a decade ago, in 1995 the first extrasolar planet around another star was detected [1]. In the meantime till today more than 150 such planets are known and their number is continuously growing [2]. We know now, that our solar system is not an exception, but that planet formation takes place frequently in the Universe. A closer investigation of those other planetary systems has only just begun.
This paper reviews some aspects of our current understanding of the formation of terrestrial planets. There is not yet an unambiguous answer to the problem. In this paper we will focus on a key stage of planetesimal formation. The standard model of terrestrial planet formation can be described briefly as follows: In the protoplanetary disk, dust particles collide and stick together [9]. As more and more stick together, larger aggregates form. Objects several meters across, and before long kilometers across, form. These objects, called planetesimals, are the "building blocks" of planets. Collisions between the

numerous planetesimals then build a fewer number of larger bodies, called planetary embryos. Eventually, one planetary embryo will have dominated and accreted most of the other bodies in its region of the disk until all the material in that region had been exhausted. Further collisions among these planetary embryos eventually lead to the formation of terrestrial planets. It is still unclear when the formation exactly occurs, but the whole process might take $10^7$ to $10^8$ years [10]. In the beginning the process of formation is based on the motion and collisions of solid particles in the protoplanetary disk. It starts with small dust particles. Collisions between the grains are relatively common, and when they collide they stick together and grow to larger dust aggregates. Usually two regimes in this growth scenario are separated, the growth of km-sized planetesimals and the growth of even larger bodies, which evolve into planets. This separation is based on the fact that motion and growth of objects smaller than approximately 1 km in size are mostly determined by the interaction of these objects with the gas. In this first stage the sticking is due to interparticular and surface forces. Once km-sized bodies formed, self-gravity gets important. Over the last decade a number of experiments has been carried out to verify this model. They show that growth of cm-sized bodies in general can be understood in terms of a binary collision model [11][12][13]. During this first stage of growth on average aggregates of same size collide very gently at mm/s or less. Once objects reach a size of several cm the impact energy is sufficiently high to initialize their compaction [11]. Then preferentially particles of different size collide at much higher velocities. A body of 1m might collide with smaller bodies at velocities of several tens of m/s. Earlier experiments on small dust aggregates show that dust aggregates would fragment in a collision at these speeds [13][14]. Therefore, it has been an open question if a mechanism exists by which high-speed collisions of dusty bodies can lead to a net growth of a larger body.
The following sections describe experiments, which relate to the first phase of evolution, the growth of planetesimals. The impact of a millimeter or centimeter dusty aggregate into a somewhat larger dusty body at several m/s to tens of m/s is what is supposed to happen in the early phase of planet formation. Our results are directly applicable to the process of planet (planetesimal) formation.

## *2. Impact experiments*

In this section we describe impact experiments, which we carried out in order to study the interaction between two dusty bodies in a collision under conditions simulating protoplanetary disks.
**Experimental set-up.** A sketch of the experiment is shown in Fig. 1. The impacts take place in a vacuum chamber (32 cm in diameter). The chamber is evacuated prior to the impact to a pressure below 0.01 mbar. The target is an aluminum tray with 6 cm diameter and 5 cm depth filled with dust and centered in the middle of the chamber. In accordance with the aim of the experiment we use two types of targets. Details of the target and projectile preparation will be given later. As projectile we use the same dust as in the target (µm-sized $SiO_2$) filled in a cylindrical holder turned upside down. An aluminum foil was used to prevent the dust from falling out. The projectile is launched by a compressed spring. The spring is pulled upwards by a string with an electric motor. Once the spring is fully compressed, a switchblade cuts the string and the projectile holder (and the projectile within) is accelerated by the spring and moves within a guide tube to approximately 15 cm above the target. A stopper stops the projectile holder and the dust projectile is launched at the dust target. The impact is imaged by a digital color single reflex camera and a digital video camera. Light for the cameras is provided by three flash lamps in two colors (blue and green) and a laser. Different positions of the light sources have been used.
**General description.** In general an individual experiment might be described as follows: A

target which has been under predefined low humidity conditions for a few hours is weighed and then placed into the vacuum chamber. The chamber is slowly evacuated to a pressure on the order of $p < 0.01$ mbar. A projectile is launched as described above to the center of the target. A few cm above the target the projectile passes a light barrier and triggers the digital camera. The camera is directed horizontally to the target surface and is operated in long duration exposure mode (4 seconds) so that just one color frame is taken for each impact. During this time the flash lamps light up at different times. The impact itself elapses in a few milliseconds. In total a sequence of four flashes (blue and green) is used to illuminate the projectile and target, which are imaged on the same frame. Thus a single color frame of the camera is used as high-speed photography. We extract different images corresponding to different times from the different color channels of this one frame. Due to the color separation, different information can be obtained, for example the projectile impact velocity, the fragment velocity, the size and the shape of the projectile and ejecta. In addition a red laser sheet is used to image the trajectories of fragments in a fixed plane perpendicular to the target. After an impact the chamber is slowly filled with air again. The target is weighed a second time after spending a few hours under the same low humidity conditions as before the experiment.

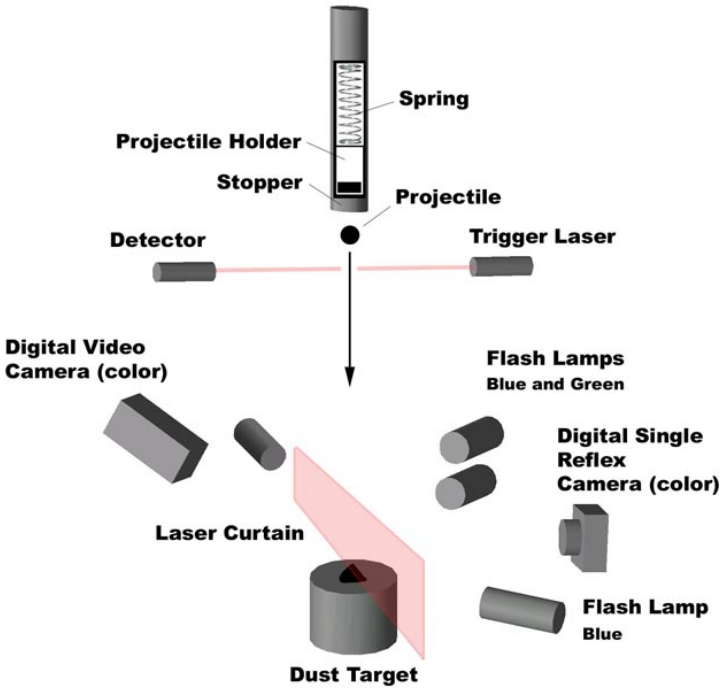



*Fig. 1. Sketch of the experiment. Taken from [15].*

**Dust.** As dust sample we used a commercial $SiO_2$ powder with a broad size distribution. Particle sizes are between 0.1µm to 10µm with 80% of the particle mass within particles of 1µm to 5µm in size. The particles have irregular shapes. The density of the bulk material is 2.6g/cm$^3$. Earlier experiments showed that the material itself is probably of minor importance for sticking of dust particles at least as similar materials like silicates are considered [11]. Thus we regard our dust as one possible analog material to model the larger fraction of particles in protoplanetary disks or the solar nebula.

**Projectile.** For most experiments we used slightly cone shaped Teflon reservoirs, which we filled with dust. The projectile was prepared in several ways. For some experiments we filled the reservoir with dust compacted manually. This dust usually does not leave the holder as one unit but breaks up into a large number of smaller dust clumps. We also

inserted dust projectiles into the holder, which were compacted outside the holder and inserted without force. This reduced the sticking of dust to the Teflon so that the dust gets out easier. Friction is less likely to disrupt the projectile mass and less mass is left within the holder after the experiment. The projectile was approximately 1 cm in size, weighed 0.2 g. and had an initial porosity of 66%.
The experiments carried out so far can be divided in 2 classes (both groups differ from each other only in the target type). In the next subsection we present the results from a series of experiments with porous targets.

**a. Impact experiments with highly porous targets**

We conducted a total of 45 experiments with impact velocities from 16m/s up to about 38 m/s. These experiments are described in more detail in [16].
**Target.** We sieved the dust sample into the target tray to get a highly porous target. For most experiments we used a mesh with 0.5mm openings for sieving. Hence targets are built up from granules that are typically 0.5mm in size for most experiments and which themselves are rather compact consisting of (sub)-micrometer-sized dust. The granular morphology of the surface is clearly visible in Fig.2a. Porosity of the targets varied between P=74% and P=88%. To study the effect of dust unit (granule) size, which is determined by the sieving mesh, we also prepared targets with 90μm and 25μm granules.
**Crater formation.** The impact into highly porous targets resulted in craters of several millimetres in depth and 2–3 cm width. An example can be seen in Fig. 2b. The depth of the crater at a given position is correlated to the impacting mass. Within the small velocity range studied and the uncertain mass densities, we otherwise cannot give a correlation between impact speed / energy and crater depth yet. Sometimes the bottom of the crater qualitatively seems to consist of a number of slightly larger dust units compared to the original target. This might be a larger fragment from the projectile but so far we have not implemented a way of distinguishing target particles from projectile particles.
**Ejecta.** We usually observed a certain amount of dust ejected from the target after a collision. Due to gravity, we can only detect fragments, which are faster than 50mm/s. Observation of particles which escape from the crater (typically depth 5 mm) is only possible, if they have an escape velocity of 0.3 m/s or more. This corresponds to approximately 1% of the impact velocity. We see no such fragments though, which can unambiguously be traced back to the crater itself. This indicates that fragments have velocities much lower than the detection limit.
A large amount of dust is ejected not from the crater but from the whole surface. The whole surface is lifted up after the impact. The amount of ejecta is larger than the projectile mass. A crude estimate is that about 10 times the mass of the projectile can be ejected. The ejecta velocity is only 0.5% of the impact velocity. The experiments imply that elastic waves are launched during the impact and that part of the top most layer of the target is lifted at the arrival of this wave. Because the individual 0.5-mm dust units are only weakly bound by a small number of contacts via surface forces between dust particles, they can easily be ejected. Probably a wave reflected at the bottom of the target tray is responsible for ejection, but further studies are needed to confirm this.
**Smaller granule size.** In order to study the effect of dust unit size in an impact we carried out the same experiments with targets, consisting of much smaller dust units - 90μm and 25μm. Even with the 20 times smaller dust granules, we have not observed a general distinction to the other experiments. The ejecta velocities are comparable to the velocities of the larger dust units.

**b. Impact experiments with compact targets**

We conducted a total of 25 experiments with impact velocities from 6m/s up to about 25 m/s. This series of experiments are described in more detail in [15].
**Target.** The targets were prepared by compressing the dust manually into the target tray. An image of a typical compact target can be seen in Fig.2c. Although the target surface seems to be very compact, the porosity is still 66%.

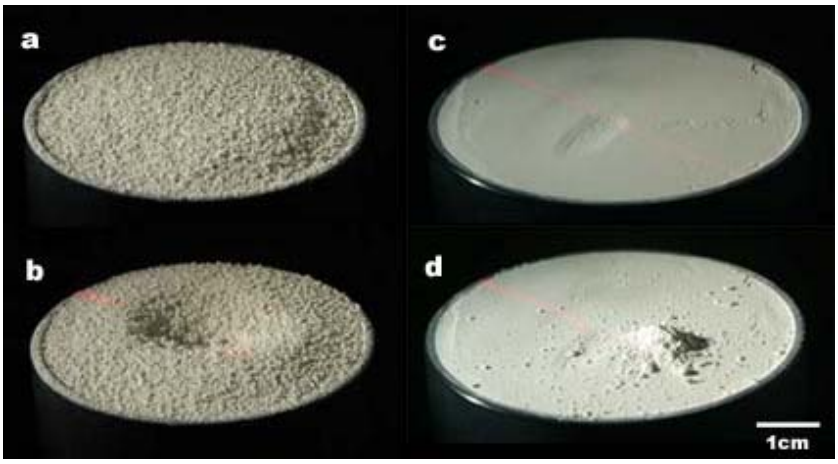



*Fig. 2.* ***a****. A porous target prepared by sieving powder with 0.5-mm mesh. The sieving results in a granular structure of the surface.* ***b.*** *Crater formed by an impact into a highly porous target at 25m/s.* ***c.*** *A compact target prepared by manually compressing the dust in the target tray.* ***d.*** *Dust pile formed by an impact into compact target at 20 m/s.*

**Pile formation.** Impacts at 20-25 m/s into compact targets resulted in a pyramid-like structure with a base comparable in size to the original size of the projectile (approximately 1 cm in diameter). The pile height was between 3 and 5 mm. A typical image of a pile resulting from a high velocity impact is shown in Fig.2d. The pile constitution qualitatively shows a similar resistance to force as the target. It is in firm contact to the target surface and is not easily removed. Besides the pile we found a number of fragments only lying on the target after an experiment rather than being stuck to it. These particles can be dropped off just by tilting the target. With decreasing impact velocity the pile changes its structure. Impacts at 15-20m/s resulted in a less compact pile structure. It can be found that projectile fragments, which surround the pile, are getting larger at intermediate and smaller speeds. At 12-13m/s we observed a transition. An impact below this velocity doesn't give rise to a pile, but the projectile survives the collision or breaks up into 2-3 big pieces. These large aggregates can be found bouncing off, but leaving an imprint into the target surface which can be several mm deep. Therefore, the target is not behaving like a solid surface but actively takes part in the impact even if it is compact. How the structure of the target is changed due to the impacts has to be the focus of future studies.
**Accretion efficiency.** One of the most important quantities for an impact with respect to the question if planetesimals can form is the mass gain/loss during a collision. We define accretion efficiency as mass added to the target relative to the impacting projectile mass. This is plotted in Fig. 3. We observed that the accretion efficiency depends on the impact speed. At highest velocities of 25m/s a larger part of the projectile sticks to the target and forms a pyramid-like structure as mentioned before. At these velocities as much as 50% of the projectile sticks to the target surface. This value can vary for an individual collision from about 30% to 70% but on average is constant down to impact velocities of about 13m/s. As the impact velocity decreases below this threshold only little mass sticks to the

target. The accretion efficiency is only 10% on average. We observed one impact (labeled no 83) just on the edge of sticking at 13m/s. The projectile was essentially intact and sticking to the target and remained sticking while the target was tilted but a mild knock on the target loosened the projectile. In another case at 8m/s a rebounding projectile caused *loss of target mass.*

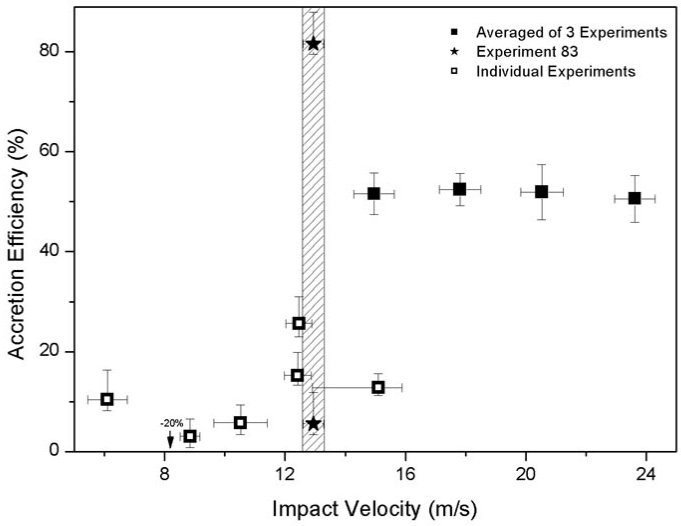



*Fig. 3. Accretion efficiency over impact velocity. Accretion efficiency refers to the mass gained by the target with respect to the projectile mass. Taken from [15]*

**Ejecta.** The fastest impacts result in a cloud of ejecta. From the outer extend of the dusty cloud in different colors corresponding to different times, the maximum fragment velocity can be determined to be 40% ±10% of the impact velocity for collisions faster than 20m/s.

## 3. Discussion of the results

The high speed impacts into targets of different morphology (very porous targets and compact targets) reported here clearly show that the make up of the target is one of the major parameters determining the outcome of a collision. The impacts studied here, are two possible scenarios for collisions in protoplanetary disks. Here we will summarize the main results of our experiments:

- If a large compact dust aggregate of mm- to cm-size collides with a larger compact dust target between 13m/s and 25m/s it will partly stick to the target. A fraction of about 50% of the mass will be added to the target on average independent of the speed as long as it is above the threshold of 13m/s ± 0.5m/s. Gravity is not an important parameter here. Experiments in microgravity would have the same outcome.
- If the same dust aggregate hits a more porous target, it will create a crater on the surface. Elastic waves can eject a large amount of material. These ejecta are very slow though. To quantify the amount of ejecta microgravity experiments are necessary.
- A projectile of mm- to cm size colliding with a compact target at speeds below 13m/s ± 0.5m/s will not stick but rebound.
- Fragments of a high speed collision into compact targets are fast with 40% ± 10% of the impact velocity.

It is often argued that high velocity impacts cannot lead to growth. However, our experiments indicate that net growth is possible in dust-dust collisions. With respect to our

results growth might be the immediate result of an impact. Our experiments also show that an impact into small, highly porous targets can eject much more mass than the projectile adds. This is yet a problem for micro gravity conditions to be studied in detail. If a collision would indeed be erosive, growth can still occur in secondary collisions by reaccreting the ejected dust. Wurm et al. [17] discuss how gas flow can return ejected particles if they are slow enough. The idea is simply that gas motion directed toward the surface of the body can drag ejected particles back to the surface. For a solid body the streamlines of the gas will surround the body. However, through a porous dusty body a certain amount of gas will flow and the streamlines close to the surface of this body will enter it. If small ejected dust particles can couple to these streamlines, they will return to the surface. The fraction of ejecta mass that is recreated by this mechanism will depend on the porosity of the target, the gas parameters, and the ejecta parameters. Wurm et al. [17] assumed fragments to be micrometer-sized dust particles slower than 0.5 m/ s. The speed of fragments ejected by elastic waves found in our experiments here is typically much below this threshold. Thus a small fragment could be recreated by gas flow.
Most important though, this is the first time that net growth in high-speed collisions has been observed and studied for dusty bodies. If planetesimals do not form any other way quicker their formation by collisional growth is very likely.

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