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Observing meter-sized dust collisions in the rings of Saturn to study planetesimal formation

Research proposal

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1 Details

1.1 Title

Observing meter-sized dust collisions in the rings of Saturn to study planetesimal formation

1.2 Research area

NWO research field	Research area
17.10.00	Planetary science
17.90.00	Astronomy, astrophysics, other

1.3 Keywords

Planet formation, planetesimal formation, dust collisions, rings of Saturn, the Saturn Ring Observer

1.4 Applicants

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2 Preface

This research proposal was written as part of the Honours Programme of the Faculty of Science of the Radboud University Nijmegen in the academic year 2017-2018. The Honours Programme is an extracurricular excellence programme for a selection of second- and third-year bachelor science students. It introduces students to scientific research and teaches them skills required for scientific research.

The programme consists of two years. The first year consists of a group project in which students from different disciplines work together to write an interdisciplinary research proposal. This is achieved under the supervision of an academic researcher of the Faculty of Science. The students immerse themselves in scientific literature to find a topic of their interest. Then they formulate a research question and write a proposal which aims to answer this question. During periodical meetings the groups present their progress to each other. In these meetings the groups get constructive criticism and advice on how to proceed. In March, the groups choose a city abroad to visit. This year London was chosen, where experts in the field were visited and ideas were discussed. Finally the proposal is reviewed by an external expert. At the end of the academic year the group presents their proposal to a general public.

In the second year of the programme the students do an individual research project in a field they choose under the supervision of an academic researcher of the Faculty of Science. This project is usually combined with the bachelor thesis into a considerably larger one.

Our group consists out of Mathematics and Physics and Astronomy students and we chose a topic within the field of astronomy: the study of planetesimal formation through observations in the rings of Saturn. This proposal was written under the supervision of dr. Juriaan Metz.

3 Summaries

3.1 Scientific summary

The process of planet formation can be divided into two parts: the formation of km-sized planetesimals out of microscopic grains and the subsequent dynamical evolution from planetesimals to planets. Currently it is not understood how from mm- to cm-sized particles planetesimals can be formed. For this it is required to understand more about the physics of dust collisions. Hence extensive experimental research has been done to dust collisions. However, the experimentally testable size range is limited by at most decimeter size. To investigate the collisions between larger particles, we here propose to study collisions in this size range in the rings of Saturn. To observe these collisions, NASA's concept mission the Saturn Ring Observer (SRO) would be used. To find out how regularly collisions between Saturn ring particles occur and what the impact of the proposed mission would be on the field of planetesimal formation, we propose to hire a PhD student to investigate the velocities and frequencies of the collisions between meter-sized particles in the rings of Saturn.

3.2 Public summary

"Where do we come from?" A fascinating question about which we know surprisingly much. However, there is still a lot unknown, for example about the origin of our home planet, the Earth. Planets are thought to have formed out of microscopically small dust particles which formed together larger and larger structures. This growth can be explained up to the size of centimeters. To date, it is still a large open question how from there, particles of a few kilometers in size are formed. To answer this question, we need to know more about the physics of dust collisions. One could study this in laboratories on Earth, however experiments with meter-sized particles are impossible in practice. It turns out that there exists a natural laboratory in our Solar System: the rings of Saturn. There, collisions of dust particles larger than a meter take place. Therefore we came up with the idea to send NASA's concept mission the Saturn Ring Observer to the rings of Saturn to observe these collisions. We propose to find out how often those collisions actually take place and what this idea would teach us about planet formation.

3.3 Samenvatting voor algemeen publiek

"Waar komen we vandaan?" Een fascinerende vraag waar we verrassend veel van af weten. Toch is er nog een hoop onbegrepen, bijvoorbeeld de oorsprong van onze planeet, de Aarde. Er wordt gedacht dat planeten zijn ontstaan uit microscopisch kleine stofdeeltjes die samen steeds grotere en grotere structuren vormden. Deze groei kan worden verklaard tot op de grootte van centimeters. Tot op de dag vandaag is het een grote open vraag hoe vanaf daar deeltjes van een paar kilometer groot worden gevormd. Om deze vraag te beantwoorden moeten we meer te weten komen over de natuurkunde van botsingen tussen stofdeeltjes. Dit kan men onderzoeken in laboratoria op Aarde. Experimenten met deeltjes van een meter groot zijn in de praktijk echter onmogelijk. Het blijkt dat er een natuurlijk laboratorium in ons zonnestelsel bestaat: de ringen van Saturnus. Hier vinden botsingen van deeltjes van groter dan een meter plaats. Om die reden kwamen we op het idee om NASA's conceptmissie de Saturn Ring Observer (SRO) naar de ringen van Saturnus te sturen om deze botsingen te observeren. We stellen voor om uit te zoeken hoe vaak die botsingen werkelijk voorkomen en wat dit idee ons zou leren over planeetformatie.

4 Introduction

Already dozens of satellites have explored the planets, moons and other bodies of our Solar System and new missions are sent out almost every year. Recently it has become possible to observe large amounts of planets around other stars: exoplanets. With all the data gathered from this, a lot can be learned about the formation of the Solar System, the planets in it and (exo)planets in general. Despite the large amounts of progress being made at this very exciting time, there are still large gaps in our understanding of planet formation which cannot be resolved at the moment.

Planets form out of the dust around a forming star. By mutual collisions and gravitational attractions, the dust forms increasingly large objects and finally forms planets. This process can be divided into two parts: firstly, the formation of kilometer sized objects, planetesimals, out of the microscopic dust particles, and secondly, the formation of planets and other large bodies in the star system out of planetesimals. The important distinction between the two parts is that gravitational attractions between individual particles only plays a role in the second part.

In the first part, there is a big gap in our understanding. It can be explained how from the microscopic grains particles of mm- to cm-sizes can form. However, it is not known how these particles can grow to planetesimal size. For example, particles in this size range tend not to stick after collisions, but bounce of each other instead.

To test the planetesimal formation theories in computer simulations, it is needed to know more about dust collisions. For this reason, numerous experiments have been done. Particularly the research group of prof. dr. Jürgen Blum of Technical University Braunschweig has improved our knowledge extensively. In the experiments they performed, dust particles of different sizes, compositions and other parameters are shot onto each other in a microgravity environment. These collisions are filmed in such a way that the resulting particles or fragments can be determined. Based on these experiments, several theories of planetesimal formation have been formed.

A problem with experiments on Earth is that there are limits to the sizes of particles one can work with. Therefore, no experiments have been done with particles larger then a few centimeters. To do this, we propose the idea of looking at the collisions of particles in the rings of Saturn. The rings of Saturn consist of large amounts of water-ice particles with sizes up to a few meters. To observe the collisions of particles in the rings, the authors propose to use a concept mission of NASA called the Saturn Ring Orbiter (SRO). This mission aims to hover very closely above the rings of Saturn to observe very small features of the rings of Saturn and even individual particles.

The proposed concept would only work if the collisions of meter-sized particles in the rings occur frequently enough to see them in a reasonable time frame. In addition to that, the collisions need to occur with high enough velocities for the collisions to be relevant to the research of planetesimal formation.

Here a proposal is presented to investigate how regularly collisions between Saturn ring particles occur and what the impact of the proposed mission would be on the field of planetesimal formation. To achieve this, one PhD student should be hired to do research to the velocities and frequencies of collisions of meter-sized particles in the rings of Saturn and find out what the impact of the proposed mission could be.

5 Scientific background

5.1 Planet formation

Stars, planets, life; everything is made out of gas and dust first formed in stars and the Big Bang. It is a very inspiring but also bold claim. The formation of these objects is not simple and a lot is still not understood. In this section a brief overview of the current theory of planet formation is given.

5.1.1 Star formation

The space between star systems, the interstellar medium (ISM), is not completely empty, but contains gas, dust and radiation. Stars can form in the densest regions of the ISM: the molecular clouds. If the mass of a cloud becomes higher than its Jeans mass, the cloud collapses under the force of gravity. In this collapse, the cloud will fragment into parts that may collapse as well. If this process continues, ultimately a dense sphere of matter is formed: the protostar.
Rotation of the cloud prevents a large portion of the material from falling onto the protostar. The material does however fall towards the equatorial plane of the protostar/cloud. Here the material from one side of the plane collides with the material of the other side, thereby decreasing the motion perpendicular to the plane. The result is that the material forms an accretion disk around the protostar: the protoplanetary disk (PPD). A part of the angular momentum is cast away by a bipolar jet: the protostellar jets. (Lissauer and de Pater [2013])

5.1.2 Evolution of the protoplanetary disk

The evolution of the PPD is determined by the redistribution of angular momentum in the disk. This change can cause for example the material to accelerate, diffuse, move outward or move inward. In the last scenario the material could accrete onto the protostar. Torques can be of magnetic, gravitational or viscous nature. At a certain moment, the disk ceases to exist; the disk clears. The gas may be removed from the faces of the PPD by ultraviolet radiation coming from nearby stars and/or the active young star. The timescale of clearing is not known, but it is believed to be $\lesssim 10^7$ yr.
Over time the temperature decreases causing the various compounds to condense into grains of microscopic size. For example, in the case of a star of solar composition, the first substantial condensates to form are silicates and iron compounds. At lower temperatures, so at larger distances from the star, water-ice and other ices can form. The outer regions may also contain pre-existing condensates of the ISM and stellar atmospheres. From these condensed microscopic grains, planets are formed. (Lissauer and de Pater [2013])

5.1.3 Growth of microscopic grains to planetesimals

The microscopic grains have to grow from a size of a few microns to that of planets which is in the order of $10^3 - 10^5$ km. This growth process is often divided into two parts: the growth from microscopic grains to planetesimals, objects of km-size, and the growth of planetesimals to planets.
The microscopic grains first grow by mutual collisions. Sedimentation of the dust particles to the equatorial plane results in collisional growth. This accounts for growth up to mm- to cm-scale. The growth of cm-sized particles to planetesimals depends primarily on relative motion. If the dust has been colliding for a long time, the particles become compact and can no longer stick to each other,

but start to bounce off each other instead; the particles have reached the bouncing barrier. (Zsom et al. [2010])
The process of planetesimal formation takes place when there is still gas in the disk. The gas is partially supported by a pressure gradient. Therefore, the gas circles the star less rapidly than the Keplerian rate, approximately 0.5% slower. Now dust particles experience drag from the gas and drift inwards to the star. Small bodies of μm- to mm-size drift slowly because they are coupled to the gas. Large bodies of km size or bigger drift very slowly because the ratio between the cross-sectional area and the mass is very small. Bodies in between these length scales drift inward fast, where m-sized bodies drift the fastest. In the terrestrial planet region, they can drift inwards at speeds up to $\sim 10^6$ km/yr. From this it can be seen that the transition of cm-sized dust particles to planetesimals has to go very quickly.
To come up with theories of the formation of planetesimals, which is an essential part of planet formation, one needs to have knowledge about the physics of interparticle collisions of μm- to km-scale. Essential parts of this area in physics are still poorly understood. The research that is put forward in this proposal aims to contribute to this by improving our knowledge about these kinds of collisions. (Lissauer and de Pater [2013])

5.1.4 Growth of planetesimals to planets

To be complete, an overview of the growth of planetesimals to planets is given.
Planetesimals are not significantly affected by gas drag anymore and are massive enough that they can have significant mutual gravitational interactions. Because of their gravity, they have an effective area larger than their cross-sectional area. Therefore they can accrete matter more easily.
If the planetesimals would stay at the same distance from the star and would not interact with other planetesimals, there would be a maximum to its obtainable mass: the isolation mass. This is the mass of all the material in a certain ring around the planetesimal. For a minimum mass solar nebula, this would be 6 $M_{☾}$ for Earth's accretion zone and 1 $M_{\oplus}$ for Jupiter's accretion zone. To obtain a mass higher than the isolation mass, one or more of several phenomena need to happen: Planetesimals have to scatter onto one another, there have to be perturbations by planetary embryos in the neighboring accretion zones or there has to be gas drag. Furthermore, radial motion of planetary embryos, called migration, may bring them into not depleted zones thereby offering the possibility to accrete more matter.
From here on several things can happen. Terrestrial planets, gas giants, small bodies and satellites of planets can form. One calls an object an (exo)planet if it is in orbit around the Sun (another star); has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape and has cleared the neighborhood around its orbit. (Lissauer and de Pater [2013])

5.2 Planetesimal formation

The formation of planetesimals is an essential part of planet formation that is not completely understood yet. In this section a more detailed overview of the research in this field is given.

5.2.1 Methods to investigate planetesimal formation

There are several ways in which the formation of planetesimals from dust particles can be investigated.
First there are observational studies in which our own solar system, exoplanet systems, protoplanetary disks and debris disks are observed. Despite the fact that individual planetesimals and smaller dust particles cannot be observed with our current technology, constraints on the formation of planetesimals can be obtained.
Secondly, one can use computer simulations. Either the global or local structure of a protoplanetary disk can be simulated. The goal of these simulations is to test theories and give new insights in these theories. These simulations require extensive knowledge about the composition and structural properties of dust particles and the outcomes of dust collisions.
A third method is to send a probe to an comet or asteroid to study their composition and structural properties. These objects are the remnants of the remaining planetesimals of the formation of our solar system. Hence, one can draw conclusions from these measurements on the composition and structure of planetesimals which place constraints on their formation. This method has only been used once: ESA's Rosetta mission to 67P-Churyumov–Gerasimenko.
A fourth approach is to use laboratory experiments to simulate collisions between dust particles. Next section will explain this in more depth. (Lissauer and de Pater [2013], Blum [2018])

5.2.2 Experimental research into the outcome of dust collisions

Experiments to understand planetesimal formation involve man-made aggregates. Because the chemical composition of protoplanetary disks can be derived from observations, the chemical composition of aggregates can be obtained. These aggregates can be closely reconstructed in a laboratory. By measuring the outcomes of the collisions between these aggregates, planetesimal formation theories can be improved and computer simulations can be made more accurate.
These experiments are done in a vacuum environment to approach the conditions in protoplanetary disks as close as possible. A drop tower or parabolic flight is used to create a micro-gravity environment for a few seconds. In most experiments, two projectiles are shot at each other and the outcome of the experiment is measured. These measurements are done by filming the interaction and characterizing the outcome of the collision. (Blum [2018])

5.2.3 Outcomes of dust collisions

Dust collisions can result in different outcomes. If the size ratio between the two colliding dust aggregates is close to unity, there are four possible outcomes of the collision of two dust aggregates.

- **Sticking:** If the van der Waals binding energy is large compared to the collision energy, the dust aggregates will stick. If the collision energy is increased, the inelasticity of the collision determines if sticking occurs.

- **Bouncing:** If the collision energy is too high to allow sticking but too low to change the structure of the dust aggregates, bouncing will occur. Experiments showed that bouncing is not only stretching the timescale of growth, but also leads to compression of aggregates which leads to an equilibrium filling factor. This is the filling factor which is reached after a large number of collisions.
- **Fragmentation:** If the speed of the collision and thus the energy is high, the dust aggregates can fragment, which means that the biggest fragments are smaller than the original aggregates. It has been shown that higher velocities cause smaller fragments.
- **Abrasion:** If one aggregate loses some mass and the mass of the other aggregate does not change, the outcome is called abrasion. This occurs when the velocity is too big to cause bouncing but too small to fragment. This has as a result that there is no growth and that the aggregates are eventually destroyed.

If the size ratio between the colliding dust aggregates is far from unity, there are three additional outcomes. In this case, the larger particle is called the target and the smaller particle is called the projectile.

- **Mass transfer:** If the projectile fragments and transfers a part of its mass to the larger projectile, the outcome is called mass transfer. This causes a (small) mass growth for the target.
- **Cratering:** If the projectile delves into the target and excavates more mass than it adds to the target, the outcome is called cratering. This causes a (small) mass loss for the target.
- **Erosion:** If after the collision the projectile has not been absorbed by the target but the target loses some mass, the outcome is called erosion. This happens when the projectile bounces and due to the impact the target loses a small amount of mass.

(Blum [2018])

5.2.4 Results of dust collision experiments

A lot of experiments have been done in recent years with varying levels of impact. The most important results are the determination of the equilibrium filling factor of silicate aggregates and the location of the bouncing and fragmentation threshold for small aggregates under certain conditions.
Experiments have been done with both silicates, which can be found in the more inner regions of a disk, and water-ice, which appears in the more outer regions of a disk. Most experiments involved silicates. These have been done using particles ranging from 1 μm to 5 cm in size with size ratios both close and far from unity. Other experiments include shooting small projectiles on a surface to understand mass transfer, cratering and erosion. Experiments using aggregates from previous collisions to find changes in their composition and filling factor after multiple collisions have also been done. (Blum [2018])
Significantly less experiments involving water-ice have been done. Most of these experiments have focused on particles ranging from 1 to 5 cm in size. A difficulty with water-ice experiments is that there are multiple possible structures of the particle possible.
The conditions in the experiments are not (precisely) the same as in the protoplanetary disk. For example, the pressure in the vacuum is much greater than the pressure in a protoplanetary disk. Also,

for water-ice particles the temperature of the disk is important for the stickiness of the particles. This is caused by the fact that parts of the particle sublimate and deposit. As a result, the outcomes of the experiments might differ from reality. As a consequence, contradictory results were found in experiments using water-ice. Despite that, these experiments showed that surface features on the particles are an important factor for the outcome of collisions. (Gartner et al. [2017])

A preliminary collisional outcome model under development at Technical University Braunschweig at the moment of writing is depicted in figure 1. Here the expected outcomes of collisions between silicates at 1 AU around a star such as the sun are shown.

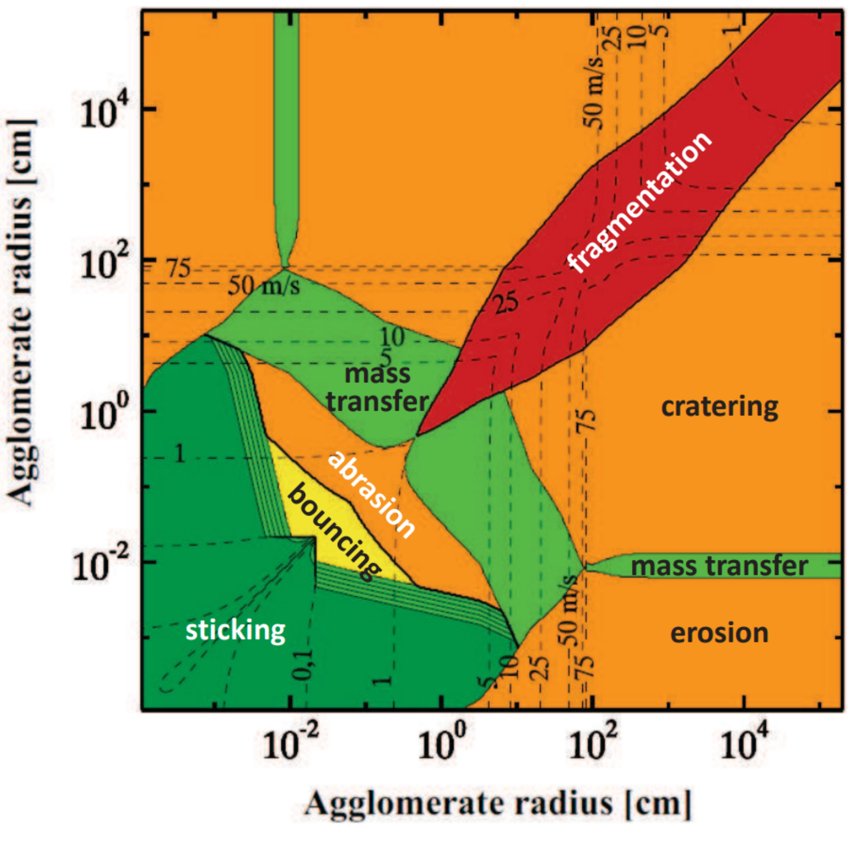

Figure 1: Depicted are the expected outcomes of collisions between two silicate particles at 1 *AU around a star such as the sun from a preliminary collisional outcome model under development at Technical University Braunschweig at the moment of writing. The axes indicate the size of the two different particles. The diagram is divided into different regions corresponding to the most common outcome. The colors indicate the net growth of particles. The greener colors indicate an increase in size after collision, while the red areas indicate that the aggregates get smaller. The dotted lines indicate the velocity of the collision. Image adapted from (Blum [2018]).*

5.2.5 Theories of planetesimal formation

Based on 25 years of experimental research, three theories of planetesimal formation were developed. Important to note is that these three theories do not contradict each other. They could possibly all be the cause of the formation of some of the planetesimals, even of planetesimals of the same star. Here the three theories are described.

Formation of planetesimals by the gentle gravitational collapse of a concentrated cloud of dust pebbles

Simulations show that if the majority of dust particles consist of siliceous material, compact aggregates of mm- to cm-size are formed. Because of the bouncing barrier, aggregates cannot grow larger and cannot reach one of the growth processes described in section 5.2.3. It was found that the maximum aggregate size depends on the PPD model, the distance to the central star and the composition of the dust. The maximum aggregate size becomes smaller when the stellar distance and dust-to-ice ratio become larger. The aggregates also become fluffier with larger distance from the star in case of smaller monomer grains and low dust-to-ice ratios. The dust aggregates in this stage of growth are termed pebbles.

Under certain conditions, the interaction between the dust and gas can cause clouds of pebbles to form. When the cloud becomes dense enough, it can collapse by the force of gravity to form planetesimals directly.

In the case of a highly-concentrated region of pebbles with a local dust-to-gas mass ratio above unity there are two major effects: Firstly, due to mutual aerodynamic shielding, the dust has an effective cross-section smaller than that of the particles combined. Because of this, the dust experiences less drag from the gas and therefore moves less rapidly radially inwards. Another result is that it moves faster in the azimuthal direction thereby catching up with individual pebbles on its orbit (and with those that reach its orbit during their radial drift inwards). This results in an increase of mass concentration over time. Secondly, the large mass concentration can accelerate the gas, which reduces the friction of the dust with the gas even more. A local minimum in radial drift can be formed, which might lead to the gravitational collapse of the pebble cloud.

This theory does not depend (a lot) on the outcome of meter-sized collisions because it uses a collapse of smaller particles to form planetesimals 'directly'. Therefore this theory would probably not benefit (a lot) from more knowledge about the physics of dust collisions in the meter size range. (Blum [2018])

Formation of planetesimals by collisional growth

First the bouncing barrier is reached like in the theory stated above. Then the gap to fragmentation, mass transfer or cratering is overcome by assuming a velocity distribution. Collisions of particles with a high enough velocity to fragment result in new smaller aggregates. Mass transfer then allows some of the dust aggregates to grow to planetesimal size.

In this theory, planetesimals form only by individual collisions between particles and not by the group behavior of the particles. Here collisions with meter-sized objects are probably important, since to form planetesimals in this way, there has to be a moment where there are meter-sized aggregates. (Blum [2018])

Formation of planetesimals consisting of sub-micrometer-sized water-ice particles

A third theory tries to solve specifically two big obstacles of collisional growth: Firstly the transition from sticking to bouncing occurs at low relative velocities, which limits the pebble size before the bouncing barrier is hit, and secondly the collision energies needed for compaction are low, which results in fast radial drift time scales. To overcome these problems the assumption is made that the material is dominated by the relatively sticky water-ice and that the ice grains are of 0.1 micron size. The first property tries to solve the first problem. The second property tries to solve the second problem because compaction is harder for smaller particles. In this model, the particles first grow in a fractal growth phase. After that the aggregates are compacted in mutual collisions, by the ram pressure of the gas and due to self-gravity.
In the fractal growth phase, increasingly larger particles are formed out of the mutual collisions of increasingly larger particles. Collisions between meter-size particles do play a role here. Therefore, it would probably be important to study these collisions experimentally. (Blum [2018])

Conclusion

Here, three different theories of planetesimal formation were described. The role of collisions between meter-sized particles differed from theory to theory. In the first theory, it is probably not that important, in the second one it is probably important and in the last one it is almost certainly important. Therefore, it would be useful to know about the physics and the outcomes of dust collisions between meter-sized dust aggregates.

5.3 The Saturn ring system

Collision experiments are difficult, if not impossible, to realize for dust agglomerates larger than 1 meter. It turns out, however, that a great natural laboratory for planet formation exists in our Solar System: the rings of Saturn. These are made up of a myriad of individual particles colliding continually, analogous to a protoplanetary disk. (Esposito [2010])

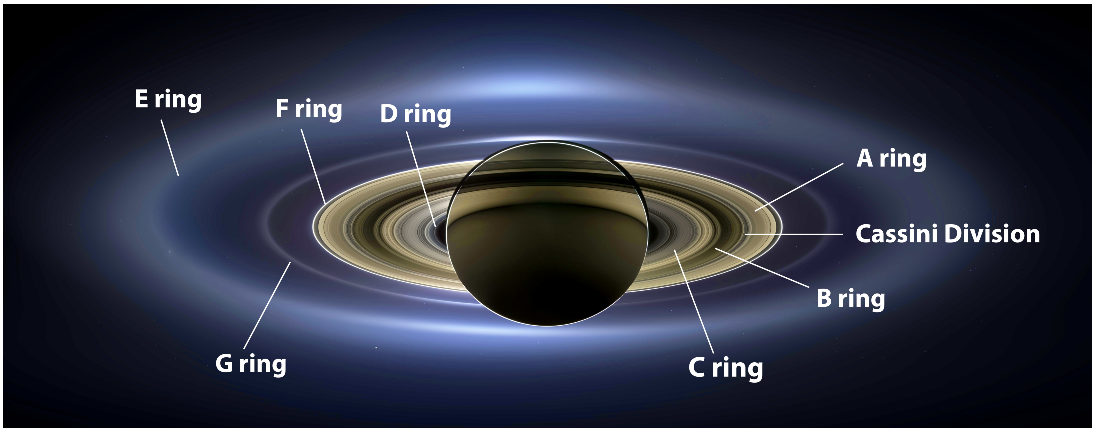

Figure 2: Saturn's rings as seen from Cassini's cameras in the shadow of the planet. The colors are enhanced from the original. The rings visible on the image and the Cassini Division are labeled. Image modified from NASA/JPL/Space Science Institute.

Table 1: Properties of Saturn's Rings. Radial location obtained from (Meltzer [2015]) and other quantities obtained from (Lissauer and de Pater [2013]).

Name of ring or other structure	Radial location (km)	Vertical thickness	Normal optical depth	Particle size
D Ring	66,970-74,490		$\sim 10^{-4}$-10^{-3}	μm-100 μm
C Ring	74,490-91,980	<4 m	0.05-0.2	mm-m
B Ring	91,980-117,580	<100 m	1-10	cm-10 m
Cassini Division	117,500-122,050	<50 m	0.1-0.15	1-10 cm
A Ring	122,050-136,770	<100 m	0.4-1	cm-10 m
F Ring	140,224		1	μm-cm
G Ring	166,000-174,000		10^{-6}	μm-cm
E Ring	180,000-480,000	10^3-$2 \cdot 10^4$ km	10^{-7}-10^{-5}	$\sim$1 μm

The system consists of multiple rings, as shown in figure 2, which are named (more or less) in order of their discovery. The bright A, B and C rings were discovered first and are referred to as the main rings. The Cassini Division separates the A and B rings. Other rings include the narrow F ring and the faint D, E and G rings. The brightness of a ring is related to its normal optical depth τ, i.e. the optical depth on a path perpendicular to the ring plane. This and other parameters, such as vertical thickness and particle sizes, vary across the rings. Observed values for these parameters are listed in table 1. (Lissauer and de Pater [2013])
The rings have been studied for centuries by ground-based astronomy and, more recently, by deep-space missions such as *Voyager* and *Cassini*. This allowed scientists to learn in detail about the complex, 3-D nature of the rings. (Meltzer [2015])

5.3.1 Size and composition of ring particles

The rings are composed of vast numbers of particles in Keplerian orbit around Saturn. The particle size distribution is often of the form

$$N(a)da = C_0 a^{-q} da \qquad \text{for} \qquad a_{min} < a < a_{max} \tag{1}$$

where a is the particle radius, $N(a)da$ is the number of particles between radii a and $a + da$, q is a fitting parameter, C_0 is a normalization constant, and a_{min} and a_{max} are the radii of the smallest and largest particles respectively. In the main rings particle sizes range between 1 mm and 10 m and $q \approx 3$. These values were obtained using the *Voyager* and *Cassini* missions by sending radio signals through the rings. (Lissauer and de Pater [2013], Esposito [2010])
Rather than being solid spheres, the particles are best characterized as temporary rubble piles. The reason for this is that they continuously collide, causing them to either grow or fragment. The particles are composed of nearly pure crystalline water-ice. This was deduced using spectroscopy. Their slightly red color shows some contamination by non-icy material. Their density is lower than that of solid ice, supporting the idea of rubble piles. (Esposito [2010])

5.3.2 Ring particle dynamics

The particles are not stationary, instead they collide continually. During collisions, the particles can stick, bounce or fragment, analogously to dust collision in experiments on Earth. The collisions are key in understanding the structure of the rings. Namely, they have two important consequences: radial spreading and vertical flattening of the disk.

Vertical flattening

A ring particle with even a slightly inclined orbit passes through the planet's equatorial plane twice each orbit, unless it collides with another particle or is diverted by the ring's self-gravity. The average number of collisions per orbit is a few times as large as the optical depth of the ring. This means that in optically thick rings, such as the B ring ($\tau \geqslant 1$), a particle collides once every few minutes. The ultimate consequence is that particles settle onto the ring plane. Thus the ring is flattened. In the main rings, the vertical thickness can be as low as 10 m. (Lissauer and de Pater [2013], Esposito [2010])

Radial spreading

A ring particle in a circular orbit in the planet's equatorial plane can collide when it catches up with a particle farther out that moves less rapidly. If the collision is completely inelastic, the particles stick. But if the collision is even slightly elastic, some of the energy involved goes into random particle motions. The ultimate consequence is a spreading of the disk. Theoretical studies have estimated the velocity dispersion to be a few millimeters per second for small particles. (Lissauer and de Pater [2013], Esposito [2010], Goldreich and Tremaine [1978])

5.3.3 Self-gravity wakes, propellers

The particles are affected by gravity in multiple ways. Because the relative motion between ring particles are low, their mutual gravitational attraction is significant. As a result, the particles clump together. This effect is visible as occultations in the optical depth of the rings, referred to as *self-gravity wakes*, which were first observed by Cassini in 2005. In the presence of a significantly large object, the particles can be swung out of their orbit. If the object is large enough, it is able to clear out a gap free of particles. Examples include the Encke gap (325 km across) maintained by the moon Pan (20 km across) and the Keeler gap (35 km across) maintained by the moon Daphnis (7 km across), both located in the A ring. If the object is smaller (10 to 100 meter across), it cannot clear out a full gap. Instead, it forms a gap shaped like a propeller. Hence these features are referred to as a *propellers*. (Lissauer and de Pater [2013], Meltzer [2015])

5.4 The Saturn Ring Observer

As stated in the previous section, already several missions have been sent to Saturn to observe the planet and its rings. However, small structures and individual particles could not be observed directly in these missions. In 2010 a mission concept study by NASA (Nicholson et al. [2010]) was published to send a spacecraft to Saturn's rings, the Saturn Ring Observer (SRO), to observe precisely these features. A visualization of the spacecraft is given in figure 3. This mission is intended to be executed after the next equinox of Saturn, which means it would be launched in the post-2023 time frame.

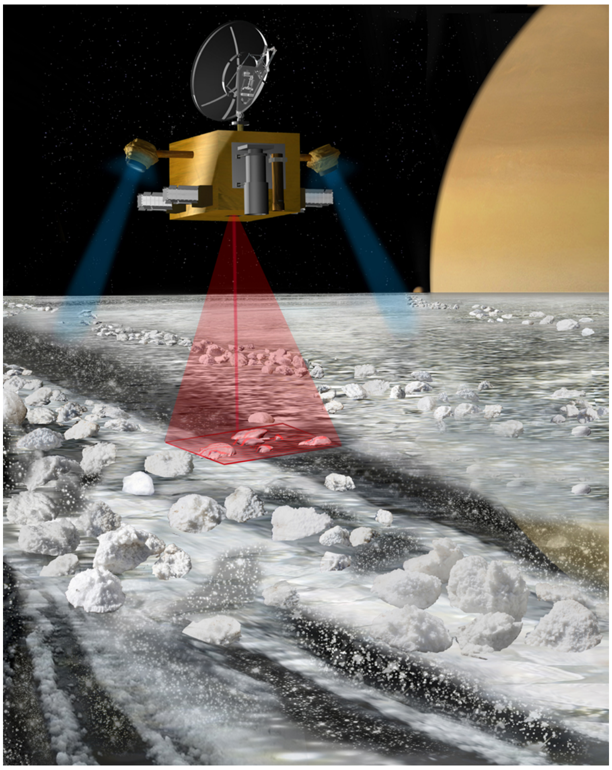

Figure 3: Depicted is a visualization of the spacecraft of the proposed Saturn Ring Observer mission hovering above the rings of Saturn. Image adapted from NASA/JPL.

5.4.1 Scientific objectives

The study describes the scientific objectives of the mission as follows:

- Characterizing the coefficients of restitution, both radial and tangential, for typical collisional interactions between ring particles
- Measuring all three components of the ring particles' velocity dispersion
- Studying the development, dimensions, packing density, and eventual dissolution of self-gravity wakes and similar structures
- Studying the detailed structure of "propellers," perturbed ring edges, density waves, etc.
- Characterizing the size distribution and spin states of the larger ring particles

(Nicholson et al. [2010])

5.4.2 Technical requirements

The spacecraft would hover about 2 to 3 km above the mean ring plane of Saturn. To achieve this the spacecraft would be propelled by low-thrust propulsion.
The spacecraft would carry several instruments. Firstly, a narrow angle camera (NAC) is used to observe the rings in the highest resolution. The current goal is to achieve a 1 cm resolution ($\sim$ 0.45 cm/pixel), although 10 cm ($\sim$ 4.5 cm/pixel) is also acceptable for the objectives of the mission. The 10 cm resolution corresponds to a view of 30 microradians at a range of 3 km. A typical 1 megapixel CCD would then have a field of view of 100 meter, sufficient to encompass one or more self-gravity wakes and more than enough to cover the mean free path between collisions. This would allow observation and analysis of individual collisions of m-sized or even dm-sized particles, if the resolution of 1 cm is achieved.
These images would be supported by the observations of a wide angle camera (WAC), which would allow the study of aggregate behavior of particles, such as self-gravity wakes and propellers.
Along with the cameras also a type of laser would be used, which would measure the distance to the ring, the ring thickness, and the vertical component of the particle velocities.
During measurement activities, the radial, tangential, and vertical velocity of the spacecraft would be near zero, relative to the average ring particle velocity. The low altitude results in a close horizon; the maximum field of view (for reasonable angular distortion) is approximately 1 radian. For a 3 km altitude, this corresponds to a view of 3 km in length. Measuring the vertical component of the velocity of the particles would be difficult because of the low velocities and the potentially irregular shapes of the particles.
At a typical particle relative velocity of 1 mm/s, a frame every minute should suffice to characterize individual collisions for the required accuracy for the mission, while also providing useful data on particle spins. (Nicholson et al. [2010])

6 Mission concept

To understand more about planetesimal formation and ultimately planet formation, one needs to do research to dust collisions. A lot of experimental research to this has been done, however, laboratory experiments with particles larger than dm-size are difficult, if not impossible, to realize on Earth. As turns out, water-ice particles of meter-size are present in the rings of Saturn and collide continually with each other. Here we propose to observe these collisions in the context of planetesimal formation with NASA's concept of the Saturn Ring Observer (SRO).

The idea is to observe with the narrow angle camera (NAC) regions in the rings of Saturn where collisions between meter-sized water-ice particles happen frequently and happen at velocities resembling those in real protoplanetary disks. The collisions between meter-sized particles are filmed. From these recordings, the relative sizes of the colliding and resulting particles are determined. The resolution of the NAC should be at the intended maximum, i.e. 1 cm, such that dm-sized fragments can be detected to get a complete image. The scale of the recording is deduced from the distance to the ring, determined by the laser, and the (constant) field of view of 1 radian. Furthermore, from the images of the recording and the time between images, the velocities of the colliding and resulting particles relative to the ring are determined. With this, the relative velocities between the particles can be obtained. If enough collisions are measured, statistics about the outcomes of collisions of meter-sized particles can be obtained from all this information. Ultimately, these statistics can be used to draw conclusions on planetesimal formation.

7 Research question

The aim of the proposed mission concept is to widen our knowledge about planetesimal formation by increasing our knowledge about the physics of dust aggregate collisions. It is questionable if the properties of the particles in the rings of Saturn are such that the particular collisions that are interesting for the purposes of the mission concept occur regularly enough. One also needs to consider if the information about meter-sized collisions is needed to solve current problems about planetesimal formation. This bring us to the research question:

Do collisions between meter-sized Saturn ring particles occur regularly enough to observe with the Saturn Ring Observer and what would these observations teach us about planetesimal formation?

To answer this question, more knowledge about the collision velocities and collision frequencies of meter-sized particles in the rings of Saturn has to be obtained. This can be done by answering the following questions:

- What are the collision velocities and collision frequencies of meter-sized particles in the rings of Saturn?
- How do the global collision velocities and collision frequencies of meter-sized particles in the rings of Saturn depend on the position in the rings?
- What are the collision velocities and collision frequencies of meter-sized particles in specific local structures in the rings?

8 Method

8.1 Outline of the research

To answer the research question described in section 7 one PhD track is needed. Here an outline of the four year trajectory is given.

8.1.1 First estimates of collision velocities and frequencies

In the literature, as described in section 5.3, there is already a lot of theory about the rings of Saturn. However, there is to the best of our knowledge no literature where the actual values of the velocities and frequencies of collisions of exclusively meter-sized dust aggregates are calculated. So the first thing to do is to investigate the current models of the rings of Saturn and make an estimate of the velocities and frequencies of collisions of exclusively m-sized dust aggregates.

8.1.2 Radial and vertical dependence of collision velocities and frequencies

If the first estimation is made, the subsequent goal is to determine the global location dependence of the velocity and collision frequency. In this research local structure and azimuthal variation are neglected. The velocity and frequency are determined for the radial and vertical position.

8.1.3 Collision velocities and frequencies in local structures

The rings also exhibit local structure, such as propellers, where the collision velocities and frequencies may be different, possibly higher, than the average collision velocities and frequencies. In the third part of the proposed research, the goal is to look at the different local phenomena in the rings and calculate the expected collision velocities and frequencies. To do this, the PhD student has to investigate the models of these local structures and probably has to do some computer modelling of these structures themselves. If the locations of the local structures in the rings of Saturn are known, it is possible to construct a map of the rings of Saturn where for each point in the ring the expected collision velocities and frequencies are given.

8.1.4 Occurrence of relevant collisions and impact on the field of planetesimal formation

Up to this point, the aim of the research was to give estimates of the different collision velocities and frequencies for the whole ring system of Saturn. To achieve the main goal of this proposal, the obtained estimates have to be used to determine if collisions between m-sized Saturn ring particles occur regularly enough to observe with the Saturn Ring Observer and what these observations would teach us about planetesimal formation.

From the expected mission time of the Saturn Ring Observer and the collision frequencies obtained in the previous parts of the research, it has to be concluded if collisions between m-sized Saturn ring particles occur regularly enough to observe with the Saturn Ring Observer. This can depend on the position in the ring system. The locations in the rings where it is possible can be determined from the calculated location dependence of the collision frequencies.

To determine what the observations of collisions of m-sized Saturn ring particles would teach us about planetesimal formation, one needs to have knowledge about the theories and (computer) models of planetesimal formation. For this reason, the aim is to find a collaborator who is an expert in the

area of planetesimal formation. A possible candidate is prof. dr. Jürgen Blum from TU Braunschweig. First of all it has to be determined if relevant collisions occur regularly enough to observe with the Saturn ring observer. One parameter that is important is the relative velocity of collisions. Firstly, the relevant collision velocities have to be determined. Secondly, based on the calculated collisional velocities and frequencies in the rings of Saturn, it has to be determined if collisions with relevant collisional velocities occur regularly enough. In this process, it can be determined what all the locations in the rings of Saturn are, where these kind of collisions occur regularly.
Secondly, based on current knowledge about the properties of the Saturn ring particles, an overview has to be given about the comparability of the properties of the Saturn ring particles, particles in experiments on Earth and particles in protoplanetary disks.
Finally, it has to be determined what the precise impact of the proposed mission on the research area of planetesimal formations would be.

8.2 Possible follow-up research

If relevant collisions of Saturn ring particles happen regularly enough and if the impact of the proposed mission concept would be considerable, then follow-up research is likely to be considered. In possible follow-up research there has to be looked at the technical and executable side of the mission concept.
For the technical aspect, it has to be found out if the anticipated measurements are possible with the measurement apparatus currently available in the concept of SRO. One can also consider to add measurement apparatus, in which case one has to investigate how to implement this. Also one has to investigate how the data from the satellite would be analyzed.
For the executable part, one has to find out where in the schedule of the mission the measurements of the collision can or have to be placed. Here one has to consider the proposed trajectory the satellite is going to follow. With the use of the information about the positions in the rings where relevant collisions occur regularly enough obtained in the research proposed here, the interesting and feasible locations can be found. One might also propose other trajectories in which the satellite will hover over the most or more interesting locations in the rings with regard to the research of dust aggregate collisions.

8.3 Timetable

The proposed research would take four years starting in September 2018 and ending in August 2022. The research would contain four parts, as described in section 8.1, each taking approximately a year.

8.4 Collaborations

For the last part of the proposed research, a collaboration with an expert in the field of planetesimal formation is required. A possible candidate is prof. dr. Jürgen Blum from TU Braunschweig.

8.5 Budget

The proposed research is a PhD track for one student and is theoretical in nature. The expected costs consist of the salary of the PhD student, the salary of the PhD doctoral advisor, the costs of the infrastructure in the university like an office and the travel expanses to conferences. A probable source of cost is the salary of the collaborator for the last part of the research.

9 Impact

In this section an overview and elaboration of the motivation of each part of the proposal is given. First, the motivation and relevancy of the field of research is explained. Then the mission concept proposed in section 6 is motivated. Finally, the aim of the proposed research is motivated.

9.1 The field of research

9.1.1 Planet formation

One of the most profound question one can ask is: "Where do we come from?" To answer this one must understand the origin of our home planet. This is the reason why the field of planet formation is so fascinating. The interest in this topic is reflected by its inclusion in the Dutch National Research Agenda. (Dutch National Research Agenda [2015])

9.1.2 Planetesimal formation

The first phase of planet formation, i.e. planetesimal formation, contains a large gap in our understanding. It can be explained how from the microscopic grains particles of mm- to cm-sizes can form. However, it is not known how these particles can grow to planetesimal size. Therefore, more research into this area is needed. Furthermore, this first phase is key in understanding the rest of the process of planet formation, because it has great consequences on planetesimal structure. The structure of planetesimals is needed to model the rest of the process accurately.

9.1.3 Dust collision experiments

To learn more about the theories of planetesimal formation, computer simulations are performed. These simulations require information on the physics of dust collisions. Therefore, experimental research to dust collisions are needed. This need is reflected by a paper resulting from the Protoplanetary Discussions conference in 2016 (Haworth et al. [2016]). In this paper, grand challenges in protoplanetary disk modeling are stated, including: "C7: Model the growth and fragmentation of solids. Develop an accurate prescription for growth and fragmentation of grains and incorporate it into 3D dynamical models of dust and gas evolution in global disc, with feedback from the dust grains to the gas." Furthermore, a collisional outcome model can be used directly to determine the likelihood of different models. For example, the bouncing barrier was located for silicate aggregates, which plays an essential role in planetesimal formation theories.

9.2 Mission concept

The collisions of meter-sized particles are important for some planetesimal formation theories. Therefore, it is important to do research on these collisions. Dust collision experiments are difficult, if not impossible, to realize for dust aggregates larger than dm-size. This is because the experiments are done in microgravity (e.g. a drop tower or parabolic flight) and in vacuum conditions. Both of these conditions are impractical to maintain for large test chambers. Furthermore, the fabrication of large dust aggregates is difficult because of their porosity.

The most suited place to learn more about m-sized collisions is the Saturn ring system. Firstly, it is known that collisions between m-sized water-ice particles occur regularly in the rings. Moreover, Saturn's rings are best understood compared to other ring systems, allowing for the most accurate estimates on the collision velocities and sizes of the particles. Finally, there already exists a proposed mission concept, the Saturn Ring Observer (SRO), which would be able to observe these collisions. The technical aspects of this mission concept have already been studied in detail.

9.3 Proposed research

The proposed research would end in August 2022. Around this time NASA will look again into the concept of the Saturn Ring Observer. In the process of deciding to continue developing this idea, NASA could use the knowledge obtained from the proposed research. In the case SRO would have large relevance for planetesimal formation, the mission could add an extra scientific objective and thus obtain a higher scientific value. If NASA subsequently decides to continue with the SRO mission and to include the proposed mission concept to the mission, this research would be important for the realization of the mission. First of all, the resolution of the camera needs to be at the maximal intended value of 1 cm to observe resulting particles of m-sized collisions. Furthermore, the exact trajectory of the mission could be chosen based on the research done to interesting locations in the rings of Saturn regarding m-sized water-ice particle collisions.

In addition to the relevance for the proposed mission concept, the research would yield insight into the broader research fields it covers. In the field of ring dynamics, it would be first to present quantitative estimates on impact velocities of ring particles. In the field of planetesimal formation it is unclear whether or not the pursuit of larger experimental collision is valuable or not. The study would decide on the scientific potential of this data and thus lay out a path for future research.

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