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SPH analysis of collisions between macroscopic bodies immersed in planetary rings

Advisor: Prof$^{\underline{o}}$ Dr. Rafael Sfair
Co-advisor: Dr. Christoph Schäfer

Author
Patricia Buzzatto Siqueira

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Patricia Buzzatto Siqueira

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CURRICULAR DATA

Patricia Buzzatto Siqueira

BIRTH	30/03/1992 - Cachoeira Paulista / SP
FILIATION	Fernando Antorio Rosa de Siqueira Alcineia Aparecida Buzzatto
2019 / 2024	Doctorate in Physics Faculdade de Engenharia e Ciências de Guaratinguetá Universidade Estadual Paulista “Júlio de Mesquita Filho” (UNESP)
2020 / 2021	Split-site doctoral Computational Physics Department and Numerical Particle Methods Group - Eberhard Karls University of Tübingen, Germany
2016 / 2019	Master in Physics Faculdade de Engenharia e Ciências de Guaratinguetá Universidade Estadual Paulista “Júlio de Mesquita Filho” (UNESP)
2011 / 2016	Bachelor in Physics Faculdade de Engenharia e Ciências de Guaratinguetá Universidade Estadual Paulista “Júlio de Mesquita Filho” (UNESP)
2008 / 2010	Technician’s license in Industrial Computing Industrial Technical College from Guaratinguetá - São Paulo State University (UNESP)

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“To shine like the sun you must burn like it¡‘
(Leona)

Abstract

Planetary rings, a common feature around giant planets, have recently been discovered around centaurs and dwarf planets. These rings often contain azimuthally confined structures known as arcs, associated with increased particle density due to corotation resonances. One well-known example is Saturn's G ring arc, attributed to the Aegaeon satellite's presence and the resonant confinement by Mimas. However, the conventional explanation of dust production by Aegaeon struggles to account for the arc's brightness within the observed period. Our study explores an alternative model of dust generation within planetary rings. Building upon that some of those systems could have macroscopic bodies, below the resolution limit of cameras and have the potential to collide, generating the visible dust or even forming new satellites. For studying the impacts between the macroscopic bodies, we used Smooth Particle Hydrodynamics (SPH) by performing detailed simulations including shock propagation, material modification and gravitational reaccumulation. Unlike previous approaches that assume gravitational regimes Leinhardt and Stewart [2011], we consider a wide range of body sizes, making no geometric constraints on collisions. This approach includes physical properties like fragmentation and porosity that cannot be addressed through N-body simulations alone. Incorporating these properties, we model the collision outcomes, exploring how bodies with such characteristics deform, compress, or fracture based on various strength models. The results of these simulations are critical for understanding the dust production and longevity of objects within planetary rings. Comparing multiple strength models ensures the accuracy of the simulations. The unique properties of planetary ring particles, including mixed ice-rock composition, high porosity, and low material strength, present computational challenges. Our research addresses these challenges by employing a hybrid method, combining detailed SPH simulations with analytical models and N-body simulations to estimate dust production rates. Overall, this work offers a comprehensive approach to understanding dust generation within planetary rings, shedding light on the dynamics and physical properties of macroscopic bodies immersed in planetary rings.

Contents

Chapter 1

Introduction

It is a well-established fact that the giant planets in the Solar System are surrounded by rings [de Pater and Lissauer, 2001]. Recently it was discovered that even dwarf planets Haumea [Ortiz et al., 2017] and Quaoar[Morgado et al., 2023], also at centaurs such as Chariko [Braga-Ribas et al., 2014] and Chiron [Ortiz et al., 2015] have this structure.

Neptune's arcs' discovery had shown that planetary rings do not always form azimuthally continuous structures [Hubbard et al., 1986]. In these arcs, the density number of particles is higher than in the neighborhood, resulting in an increment of the detected brightness (or a more pronounced drop in the case of stellar occultations). Also, Cassini spacecraft data revealed that Saturn's rings also have some denser regions, for instance, the arcs of Anthe and Methone [Hedman et al., 2009b]. The most widely accepted mechanism for the existence of arcs is confinement through corotation resonances. This kind of resonance creates stable points so that the particles are azimuthally confined, thus increasing the surface density Hedman et al. [2009a].

Usually, arcs appear brighter when viewed at higher phase angles. This indicates that the particle size distribution that forms these structures is dominated by grains of dust (typically from 0.1 to 10 μm). The arc formation process is generally related to the presence of a satellite. For instance, the G ring arc whose formation is credited to the small Aegaeon satellite and its confinement is due to a corotation resonance with Mimas [Hedman et al., 2007].

Moreover, according to Hedman et al. [2007], collisions with Aegaeon could generate the micrometric particles that populate the G ring. However, Madeira et al. [2018] showed that due to the solar radiation pressure, the dust particles ejected from Aegeon are lost on a scale of a few decades, while the production mechanism requires at least 30,000 years to accumulate enough mass to account for the arc's brilliance.

A more elaborated model of dust generation to explain the formation of the G ring arc has been proposed in Lattari [2019], and it fits with the data collected during a Cassini flyby. The data indicated the existence of a population of macroscopic bodies immersed in the arc, which, although large, would be below the resolution limit of the cameras. These bodies may eventually collide with each other and, depending on the collision parameters, they can fragment (generating more dust) or merge (creating new satellites).

To test this hypothesis, Lattari [2019] conducted N-body simulations to analyze the collision between macroscopic bodies. The collisions were computed using the semi-analytical treatment proposed by Leinhardt and Stewart [2011], which employs a simplified model considering only the collision geometry and the relative speed of the objects, without accounting for information regarding the type of material or internal properties of the bodies.

However, these physical properties cannot be modeled with N-body simulations. A more suitable method to model this kind of system is through hydrodynamic codes, such as a meshfree Lagrangian method, smoothed particle hydrodynamics (SPH), pioneered by Gingold and Monaghan and Lucy in 1977. This method offers the flexibility to model the internal properties based on various parameters, enabling the investigation of material responses across different pressure and temperature ranges.

Bodies within planetary rings typically range from centimeters to a few tens of meters in size. However, existing collisional models in the literature often presume a gravitational regime, implying a minimum size of 100 meters. Therefore, caution is necessary when employing equations like those presented by Leinhardt and Stewart [2011], particularly regarding their validity for smaller bodies. Not all bodies within planetary rings necessarily adhere to a gravitational regime, as fragments of varying sizes can exist in a non-gravitational state Benz and Asphaug [1999]. Moreover, this project aims to analyze collisions across a broad spectrum of body sizes without imposing constraints on collision geometry, as such variations naturally arise from trajectories generated by N-body simulations.

In this study, we will explore certain physical properties of bodies that influence collision outcomes, such as fragmentation and porosity. The efficacy of deformation mechanisms hinges on assumed strength, acting forces, and how bodies with such properties compress or fracture based on strength models. These models are integrated into numerical simulations, aligning closely with outcomes observed in laboratory experiments and explaining orbital dynamics observed through observations. Given that simulation outcomes directly correlate with strength models, it's crucial to compare all available models to derive meaningful results.

The planetary ring's expected physical properties, such as its composite nature comprising ice and rock, considerable porosity, and limited material resilience, present notable computational complexities. Addressing these challenges requires the development of a methodology capable of facilitating in-depth modeling of shock propagation, material alterations, and gravitational reaccumulation. Moreover, this approach must ensure efficient simulation execution within reasonable timeframes while maintaining minimal errors. To achieve this objective, the study will incorporate comprehensive simulations encompassing shock wave dynamics, material transformation processes, and gravitational mass reaccumulation. These simulations will employ a hybrid hydrocode for analyzing small celestial body disruptions during collisions, coupled with the computational techniques of the N-body code.

The outline of this thesis follows this structure: the next chapter explains planetary rings, their features, theories concerning dust production, and collisional models. In the introductory sections (2.1 and 2.2), we introduce systems that may have macroscopic bodies and discuss the primary source of dust production. We explain how to calculate it and understand the possible production mechanisms required to accumulate enough mass for the arc's brightness. The last introductory section (2.3) presents the analytical collision model by Leinhardt and Stewart [2011], one of the most widely used and accepted models. Consequently, we aim to compare our numerical results and verify the validity of macroscopic bodies. Chapter 3 explains the numerical method used in our project, specifically the SPH method based on the MILUPHCUDA code [Schäfer et al., 2016]. Within this chapter, we showcase the primary models necessary for implementing or testing the code. Finally, a dedicated chapter (3) delves into numerical simulations using SPH. We start by presenting numerical tests defining our initial conditions, followed by a comparison of collisional ice bodies with laboratory results. Eventually, we apply these methods to Saturn's G arc and compare our findings with the Leinhardt and Stewart [2011] model. Our analysis includes calculating dust production, identifying fragments remaining in the system after collisions, and outlining the properties necessary for moon-like formations, such as Aegeaon.

Chapter 7

Final remarks

The studies of the dynamics of planetary rings are usually based on numerical simulations of N-bodies, where collisions involving small particles are generally considered constructive, this means that they generate a new body whose mass is the sum of the masses of the particles involved and the total linear momentum is preserved. This approximation works reasonably well for the up to a few meter-sized bodies. However, observations have shown that the rings are mainly formed by centimeter to meter-sized particles. This is supposed to be a consequence of inefficient models of generation of dust and formation of moonlets, in which two bodies collide and result in another body without a part of the matter being able to be lost.

We reviewed the numerical models available and implemented new methods to analyze the physical properties of those macroscopy bodies. In this sense, we performed simulations based on simulations of SPH and we analyzed the numerical errors related to the limited of the models due to the size of the bodies used in the system. Additionally, we conducted simulations to validate and compare our findings with laboratory experiments, particularly those involving plastic models representing rigid and porous ice. This comprehensive approach aimed to refine our understanding of planetary ring dynamics and particle formation.

The efficiency of all the mechanisms described in this project relies on the assumed strength of the small body in which these mechanisms act. That shows the importance of the definition of strength is so clear and we must address this problem by defining the strength for different kinds of materials inside the planetary rings. The proper strength model describes the disruption of a small body compatible with laboratory experiments. This is the concern to implement and compare different models in the simulations to realize more realistic experiments.

It was important to perform simulations to define the SPH initial conditions for our real systems.

This process reduced the numerical errors, thereby improving the accuracy and reliability of the simulations. We compared the plasticity models available at Fish and M. model is more suitable for the material we are interested in. Working with a plasticity model which takes into account parameters like friction angle and cohesion, can make outcomes more likely according to the laboratory results. Moreover, the SPH particles carry the physical properties of the bodies, so their initial conditions and arrangement can affect the outcome of a simulation. For this reason, we tested different particles' geometry and using the concentric shells produced by SEAGen script reduced the numerical errors, avoided symmetry effects, and the energy stabilizes faster not causing any unexpected damage. Along with particles' geometry, we studied the possibility of a simulation to overestimate the density and it was found that using 55 neighbors was the best fit.

In this work, we also compared our results with the semi-analytical approach and found a divergence of SPH fragment outcomes with Leinhardt and Stewart [2011]. This can be due to the fact Leinhardt and Stewart [2011] method considers only objects in the gravitational regime, and the macroscopic bodies of the arcs have sizes that are in the boundary or even outside of this regime of this regime. For the porous case there was a more clear difference with the prediction of the outcomes from Leinhardt and Stewart [2011], since such property cannot be taken into account.

Then using the defined initial conditions, we performed simulations to study the collision between the possible macroscopic bodies at the G arc of Saturn. Using short-term evolution of the system using N-body simulations, we used SPH to simulate the collisions obtained at N-body and then determined the distributions of the mass, velocity, and orbits of the ejecta. The fragments produced from the SPH simulations were returned to the N-body simulations to analyze if they would remain in the G arc. The fragments with higher velocities tend to make the fragments escape from the system. However, we found that bodies with porosity changed the outcome and generation of dust because they lose energy to crash the porous and deform until start to crash, but the general percentage of lost mass is similar to the non-porous case.

We studied the effects of varying parameters, such as object sizes (both target and impactor), differences in material, porosity and also different geometries and impact velocities. For then be able to understand how those parameters influence dust production. Our next step is then introduce a surrogate model for N-bodies simulations that gives fast, reliable answers for the masses and velocities outcome from collisions between bodies in rings, as a function of the colliding masses and their impact velocity and angle.

Altogether the project is defined by collision outcomes, the physical properties of macroscopic bodies embedded in rings, by implementing into the SPH simulations models that agree with laboratory experiments. Finally, the dynamics, production of dust production could be studied through the grid of simulations we performed, varying physical properties, like sizes and densities, and the impact parameters, such as impact angle and velocity.

This project can also be applied to other systems, using our hybrid method with SPH and N-body simulations, which possibly have macroscopic bodies. Likewise as our presented study for the G arc, through investigations of impacts between interplanetary dust particles on nearby satellites' surfaces, that can not produce sufficient particles to replenish the dusty ring population, we evaluate the possibility for this system to have macroscopic bodies, by performing numerical simulations using N-bodies integrations, to analyze the dynamics of a sample of dust and bodies under the effects of disturbing forces, drag forces, and the gravitational effects of nearby satellites. Then perform SPH collision to understand the physical properties of those bodies and their possible densities, cohesion, fragmentation, or porosity. Then finally, match the results using macroscopic bodies with the profiles of the rings from the observations data, to prove those macroscopic bodies are sufficient to maintain the replacement of visible dust particles in the rings.

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