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Report on the PhD thesis by Mr. Pavel Ševeček

Dear Dean Rokyta,

please find attached my report on the PhD thesis "Simulations of asteroid collisions using a hybrid SPH/N-body approach" by Mr. Pavel Ševeček, supervised by doc. Mgr. Miroslav Brož, Ph.D.

It was a pleasure to read and review this excellent thesis.

Sincerely,

Christoph M. Schäfer

Report on the PhD thesis
"Simulations of asteroid collisions using a hybrid SPH/N-body approach"

Author: Pavel Ševeček
Supervisor: doc. Mgr. Miroslav Brož, Ph.D.
Study programme: Physics
Specialisation: Theoretical Physics, Astronomy & Astrophysics
Department: Astronomical Institute of Charles University
Reviewer: Christoph M. Schäfer

The main topic of the thesis by Pavel Ševeček lies in the field of asteroids. In particular, the goal was to simulate collisions between objects in the size regime of asteroids, that is, gravitationally interacting bodies with an internal material strength. This is a highly manifold challenge since different physical processes are important and have to be considered. On the one hand, the classical N-body problem, where masses interact purely gravitationally, and on the other hand, the requirement to model solid, rocky bodies with a material strength and fracture. In order to tackle these problems, Mr. Ševeček developed the completely new program code OpenSPH in the programming language C++ which uses a hybrid SPH/N-body approach[1], and applied the new code to selected astrophysical problems related to asteroids.

The very first part of the thesis is a short preface which introduces the reader to the overall subject of the thesis and motivates the need for numerical simulations. The most important publications of the past years are cited.

The second chapter is a comprehensive, thorough introduction into the Lagrangian method smoothed particle hydrodynamics (SPH) and the hybrid SPH/N-approach that is implemented in Ševeček's code. Especially this chapter 2 is a striking piece of work and appears textbooklike. Future generations of PhD students dealing with SPH will most certainly be able to benefit from the description and completeness of this chapter: The numerical method is described in great detail and most of the advantages and disadvantages and recent novelties of the scheme are outlined. The first part of this second chapter contains the basic principles of the general SPH method as developed by Monaghan, Gingold and Lucy in the seventies, followed by the newer and more modern improvements of the scheme. The next part of the chapter is used by Mr. Ševeček to present the equations for viscous fluids and solid bodies that are solved using SPH, followed by the description of the density evolution and special technique of discretization to conserve energy. A very important ingredient in SPH is the so-called artificial viscosity which is required to deal with discontinuities such as shock waves and which is explained in the subsequent section of the chapter. Again, Mr. Ševeček's comments and exemplifications are precise and detailed. The remaining sections of the second chapter deal with the physical models, that is the equation of state which was used to model the asteroids, the rheology model which is used to model plasticity, added by acoustic fluidization, and finally the fragmentation model after Grady and Kipp to model brittle fracture, which completes the SPH physics part. The next subsection covers the problem of generating initial particle distributions for SPH simulations. Mr. Ševeček describes different techniques such as lattice-based distributions, parametrized spiraling, and blue noise sampling which can be used to create initial data. In order to obtain an equilibrium initial particle distribution for gravitating objects, additional special care has to be taken to achieve a stable physical state where the pressure gradient compensates for the gravitational force in a hydrostatical equilibrium. The remaining part of the chapter addresses the handling of self-gravity, that is the gravitational forces between the SPH particles themselves, and additional important notes on the implementation details of OpenSPH.

[1] The code is freely available via `https://github.com/pavelsevecek/OpenSPH`

Chapter 3 contains the typical, or even standard, tests that every new hydro code has to pass: Sod's shock tube test in 1D, Sedov's point explosion in 2D, the simulation of the Kelvin-Helmholtz instability for the hydrodynamical part of the code, followed by tests for the perfect elastic solid part of the code, the colliding elastic bands test, the rotating solid rod test. All these tests are explained in great detail and a potential reader has access to all required information to pursue these tests on her or his own. The validation of the material models is presented in two following subsections in the chapter: The cliff collapse simulation to test the Drucker-Prager rheology model for granular media, and a fragmentation validation test in which the results of a laboratory impact experiment are compared to the simulation. The chapter closes with a convergence test, in which the laboratory experiment is simulated using various different numbers of particles. The results are all very satisfying, showing that OpenSPH is capable to tackle astrophysical problems in the context of asteroids.

The following three chapters 4 to 6 are review chapters for three papers that have been authored and co-authored by Mr. Ševeček. The base for the research for all three papers is the hybrid SPH/N-body code OpenSPH.

The first research project investigates small (diameter of 10 km) asteroidal breakups and was published in Icarus. In total, 125 hybrid SPH/N-body simulations have been performed and analysed. The authors, lead by Mr. Ševeček, derive new parametric relations describing fragment distributions, which can be used in Monte-Carlo collisional models.

The second research project investigates rotating targets and angular momentum transfer and was published in Astronomy & Astrophysics. For this project, special care had to be taken since SPH does not conserve angular momentum if the extension for linear consistency is applied. The authors, also here lead by Mr. Ševeček, find the interesting outcome that collisions cause a systematic spin-down of the asteroid-population.

The third and last research project study the impact that formed the Hygiea asteroid family. The study was published in Nature Astronomy. Mr. Ševeček and his co-authors ran a number of hybrid SPH/N-body simulations from which a few match the observed SFD closely. In the study they anticipate the discovery of several new dwarf planet candidates when 3D shape models become available for trans-neptunian objects with diameters larger than 400 km.

In the seventh and last chapter, Pavel Ševeček provides a short summary of his research during the course of the PhD thesis and gives an outlook for further applications of the OpenSPH framework.

As already mentioned in the beginning of the report, the thesis is very well written and especially the second chapter could be used as an introduction to SPH in a lecture. There are no major or minor issues that have to be addressed. The language and figures are of very high quality ("journal-ready"), the research projects are well defined and described. Additionally, I want to stress that Mr. Ševeček has not only developed a whole new SPH code from scratch, which is already a considerable amount of work, but additionally has implemented a visualization tool to analyse the results from the simulations. The material models and numerical schemes in OpenSPH are all state-of-the-art, and the results presented in his thesis are original research applications, contributing to the astrophysical understanding of our Solar System, especially the formation and the evolution of asteroids.

I recommend without hesitation that the candidate is awarded the doctoral degree **with the best possible grade**.

From the personal point of view, I would be interested about Pavel's plans to port his OpenSPH code to multiple nodes, e.g., distributed cluster computing to simulate even higher particle numbers.