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Simulace galaktické dynamiky a jejich využití ve výuce fyziky

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Teorie vzdělávání ve fyzice

CONTENTS

1 Thesis objectives

This work aims to create the self-teaching educational-research project involving many-body computer simulations with the objective of studying galaxy dynamics.

The main goal of this work is to create the self-teaching educational-research project, which will guide a student through the numerical models and computer simulations of galaxy dynamics. It will show in detail a numerical construction of galaxy models and how these artificial galaxies may be evolved with the computer simulation.

Output at the technical level will be a study material for the education of galaxy dynamics showing the development of many body computer simulations step-by-step. Output at the pedagogical level will be the project in computational astronomy with a self-teaching approach. Output at the level of general interest will be animations suited for classic school education and the popularization of astronomy.

Dissertation itself is composed of two parts. Chapters 1 and 2 handle the theoretical pedagogical framework of the thesis and chapters 3–8 contain technical material with my original contribution to the simulations of galaxy dynamics.

The final idea is to lead students into the understanding of the principles behind the many body simulations for galaxy dynamics – reading the technical part of the thesis, experimenting with galaxies, letting them collide, taking a look at the source code, modifying it and developing new modules for it.

The aim of this thesis is to develop numerical model of galaxy dynamics, which permits future maintenance and modification by non-expert programmers. I do not assume that students reading the technical part of the thesis are mathematical or programming experts. These skills will be developed during the creation of models.

1.1 Experimental methodology

I have used computer modeling and simulations throughout the dissertation. Many-body simulations were evolved for up to hundreds of thousands timesteps at different resolutions that allowed me to study galaxy dynamics accurately with modest computational resources. All galaxies were modeled self-consistently as fully three-dimensional collisionless many-body systems. The galaxies were evolved with an algorithm containing no geometrical or spatial limitations.

1.2 History and state-of-the-art

Before the invention of reading and writing, people were taught through the direct and informal education of their parents, elders, and priests. They learned how to survive against natural forces, animals, and other humans. By using a language, people learned to create and use symbols or words to express their ideas. Still, their thinking was limited to the knowledge given to them by their teachers and a limited amount of pre-selected books.

Ongoing technological development is providing means for new methods of education. Students can freely choose what to study without any limitations. Study materials are available not only for general areas of science, but also for specialized fields due to self-teaching educational-research projects. Unfortunately, the educational texts joining education with state-of-the-art research are very young and there is just a small amount of them. Hut and Makino (2006) are developing similar ideas of educational-research project focused on the simulations of stellar clusters. The self-teaching educational-research project for the simulations of galaxies did not exist until now. It is produced here for the first time.

2 New pedagogy

Technology, the use of scientific knowledge for practical purposes, has a profound impact on the way we live and on the quality of our lives. A powerful method of science and research endeavor brings us every aspect of our comfort. People should know merits behind their everyday lives brought by the science. A science teacher that serves as a local expert in some specialized field of the science should teach others about these advantages.

Until the 18th century, great scientific discoveries were not explained nor popularized. Scientific knowledge was gathered for its own sake and it had a few practical applications. Scientific knowledge should be disseminated to a wider audience of people, even if they are not directly involved in scientific research. Scientific work should be made clear from its foundations. In an open and democratic society, science should be accessible to everyone and not become an exclusive domain of specialists. All people are able to understand science; scientific knowledge should be available to all of them. When new findings are not transferred to people, they lose their significance; instead, a mix of pseudoscience emerges.

The role of a traditional teacher in every educational system is to transform the majority of students from a state of pure desire to receive good grades and succeed (secondary motivation) into a state of desire for the knowledge itself (primary motivation). From my experience as both a student and as a teacher, I believe that teachers at lower educational levels should always serve physics in the basic curriculum in an easy and interesting way, together with a classical lecturing.

Astronomy is probably the most visually exciting science and it can capture the attention of those students, who would otherwise hesitate to choose a physics course (seminar, field of study, etc.). The universe has interesting topics to study for nearly all students without a difference in age or abilities. The universe is the source of inspiration, unusual images and information, which can capture the students' attention and awake other questions and curiosity. However, studying the universe is more than looking to exciting pictures of space with a great aesthetic experience. It also answers the most fundamental questions for which every human being need to know an answer. From this point of view, the knowledge of general physics might be more interesting. Students can be motivated by the space science (Dunkin et al., 1997).

Very little of this curiosity of physics is present in the traditional physics course. Students usually associate learning physics with a rote memorization of laws (Redish and Wilson, 1993).

2.1 Self-teaching with educational-research projects

Primarily motivated students can easily start their own education. *Many people think of education as something that occurs in a school or classroom. However, knowledge-eager students can gain additional skills behind the walls of school. This self-teaching approach in the "New Pedagogy" is based on motivated people studying outside the general compulsory education.* For example, a study conducted in the United Kingdom revealed that one in six people undertakes a learning project outside of formal education system (Brockett and Hiemstra, 1991). Students should have a chance to acquire other knowledge of their interests, which is not of the interests of their teachers through the self-teaching approach – from an arbitrary area of art or science. This approach is the part of lifelong education. Anyone who does not engage in the self-education, voluntarily or not, lags behind the demands of the time (Ruvisnky, 1986).

The self-teaching project requires an active approach from the student. Students are learning when they are active and remember information they understand. "Learning is not a spectator sport" (Svoboda et al., 1999). Students are not learning only compiled knowledge, but they are *constructing* and updating a memory map of abilities through their own activity and effort. Students are subsequently able to apply the acquired knowledge in other situations. Students remember competences they gathered through their own endeavor and effort. Students should look for information over the Internet and classify them independently. Students should learn to read technical writings of others. In educational-research projects, students are developing a whole spectrum of cognitive abilities – thinking and reasoning, memory and learning, attention, perception, judgment, imagining, problem solving.

Every student as a human being is *different*, with different abilities, interests, needs, different learning curve and speed. The self-teaching approach has many *humanistic* effects leading to the student's *individual* personal development. The self-teaching gives to the student a greater degree of self-fulfillment, the liberty of action and the power of control. The student has a positive enjoyment from an education. This will eventually start positive student attitudes towards the science and high technology. A free choice raises a motivation and the education is more meaningful. The education is spontaneous and naturally rises from individual abilities, interests and needs. Such activity, arising from personal interest leads to a concentrated work and self-nurture. Output of such a creative education is a product, which can serve as the learning material for others – the student is in the role of the teacher of others. On the other side, the student is completely responsible for her or his actions and asserts.

A teacher usually plays a leading role and determines the speed of education. I am convinced that it is insignificant to go sit on a lecture and write down derivations lasting several pages. Better scenario is that a tutor should give to the student a complete derivation with all related thoughts. The student should be provided with educational materials showing problems from various viewpoints. The student then walks through the educational materials by the self-teaching approach through a trial and error. For this purpose, a recorded form of language is better than a spoken language, because students can jump over things known to them, and return back and read over and over again things they do not understand.

Educational-research projects from various areas of the science are on the Internet and should be more of them. I would like to encourage others to make their software and thoughts free so that everyone can learn and appreciate. Accompany your scientific software with documentation and publish it on your webpage so it will be for the greatest possible use to public. These projects contribute to the globalization and democratization of education and research.

Piet Hut and Junichiro Makino started the initiative Open Knowledge (Hut, 2006) based on the educational-research project. Basic underlying goals of this initiative are namely

- self-contained description: a high-school student should be able to start at page 1, and work her or his way through the educational series,
- provide all the details needed when starting from scratch,
- walk through the actual process of learning through trial and error,
- audience: anyone interested.

I am convinced that education will evolve closer to an ideal model of total differentiation or individualized learning together with forms of social and interpersonal education. Apart from the latter, thanks to the development of computer and information technology, there is a glimmer of light for the individualized education with self-teaching educational-research projects and e-learning programs made-to-measure student's needs right now.

2.2 Research method as a form of education

Teaching methodologies can be arranged on the basis of relative amounts of the teacher's and student's contribution to the education. A similar division depends on how much the teacher put emphasis on learning and how much on student's personal individual cultivation. At one end of the spectrum is the teacher as the controller of the class and the facilitator of knowledge. At the other end is a free discovery method, which is characterized by students exploring subjects of their own interest in ways most comfortable to them.

The research method of education requires on students individual problem solving for an integrated problem assignment. Teacher's activity is suppressed in this form of education. Teacher's task is to identify and select right problems that evoke a student's complex creative behavior, and let them select their own decision procedure. Teacher's role is no longer central; the teacher becomes an adviser. Teacher's duty is to stimulate and cooperate with the student, not just examine the student's knowledge.

The research method of education is a method of active learning that develops complex intellectual abilities in connection with a work on a complex and uneasy project. The active education-research demands on the student thinking not only about technical matters of the project, but also about activities encompassing this project, such as a stress, time schedule, relaxation, sport and free time usage.

The research method of education requires classical forms of perception and reproduction, which are directly incorporated inside it. However, the research method also requires the discovery and fixation of complex cognitive operations and the interiorization of algorithms to solve problems. The research method is more demanding than a formal learning process in the education system and involves various activities and resources.

The self-teaching in research method also has *social aspects*. The self-teaching does not mean that all learning will take a place in isolation from others. Although students work in part independently, they must always *cooperate* in larger educational-research projects. Students must participate in study groups and the overall success of project depends on each member of the group. Students must develop communication skills and use a global consciousness to solve problems with others on the Earth via the Internet.

I am convinced that students must be exposed to research level problems at an early stage of their education in order to sustain a continuous advancement of technology and science in long terms. On the other hand, education is a complex system concerning very complex people. The research method of education is not suitable for every educational situation or every student on every school. It depends on the teacher how wisely she or he will choose the methods of education.

2.3 Application

Therefore, I propose a four-level educational architecture (Figure 2–1), which is divided into four levels. The first level is for casual students who are interested in nothing more than in animations that are suitable for public presentations. Students in the second level will use an existing simulation program, change input parameters and look for results. Third level students will be more interested and will read technical information written in the second part of this thesis to get a better insight. The four-level architecture culminates with students reading, programming, analyzing and expanding galaxy dynamics simulations, and with a deep understanding of numerical simulations.

Students in the first level are only occasional people caught by a nice animation. Since galaxies evolve very slowly in comparison with one lifetime, it is hard to see any changes in real galaxies. Galaxy simulation allows to actually see a model galaxy evolving with student's own eyes, something that is not possible in the real universe, but what is actually happening. The second level is for users who are interested only in using galaxy models and simulations, executing the software applications. Having some deeper doubts, the user might want to know how galaxy dynamics simulation works: its concepts, routines and different approaches.

The level 3 user will be interested in reading the technical part of this work. It focuses on the theory behind the galaxy dynamics, and on algorithms used in the simulation software. In each chapter, there are explanations of the algorithms. In addition, the user can access the project's web site, where all materials including codes and animations regarding this work are listed and can be downloaded. If the student is willing to contribute, she or he will also look at commented source code, to better understand how the software works.

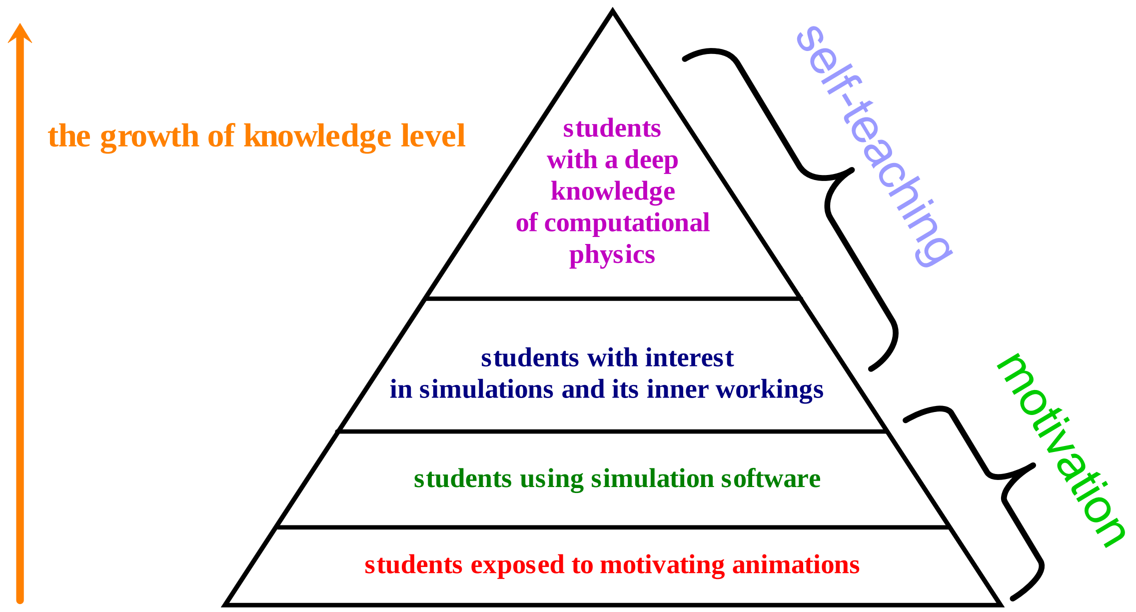

Figure 2–1: The four-level educational pyramidal architecture that is grounded on the solid foundations of primary motivated students. Upper levels contain students with the high interest and understanding of numerical simulations.

At this point, the student will be able to develop a new module (which could be an assignment, for instance) or upgrade the old ones. This is the level 4. People who get into this level become developers that extend the code and make the part of the galaxy dynamics worldwide team. It is our desire that all users reach this level, but no one is obliged to do so. The final goal of this four-level user approach is to provide to the student a means of learning simulations of galaxy dynamics in a whole way. The student will be able to read about it, understand its principles and further expand it.

Now numerical galaxy dynamics should not be a mystery to the student, and the gap between the concepts being taught at classes and the state at the research level will be minimized.

3 Simulation example: the Milky Way galaxy system

Our own Milky Way galaxy is still in the process of galaxy evolution, growing through eating smaller companion galaxies. The Milky Way is currently accreting its small companions, the Magellanic Clouds and numerous nearby dwarf galaxies. The Milky Way's disk is thickening as a consequence of accretion of smaller companion galaxies (Buser, 2000).

Large and Small Magellanic Clouds

The largest companions of the Milky Way galaxy (MW) are the Large and Small Magellanic Clouds (LMC, SMC). These galaxies orbit the MW every few billion years. Tidal forces of the MW extracted from the Clouds a circumpolar stream of gas known as the Magellanic Stream that trails the LMC and SMC in their orbit around the MW and stretches over 100 degrees in the Southern Sky.

	LMC	SMC
mass within radius	$8.7 \cdot 10^9\ M_\odot$ †	$2.7 \cdot 10^9\ M_\odot$ ‡
radius	8.9 kpc†	3 kpc‡
position [kpc]	(–1.0; –40.7; –26.3)*	(14.8; –36.1; –41.9)*
velocity [$km \cdot s^{-1}$]	(41.0; –200.0; –169.0)*	(60.0; –174.0; 173.0)*

Table 3-1: Mass, position and velocity of the Large and Small Magellanic Clouds. Parameters (†) from van der Marel et al. (2002), (‡) from Harris and Zaritsky (2006) and (*) from Kroupa and Bastian (1997).

Positions and velocities adopted for the LMC and SMC are given in Table 3-1 in Galacto-centric coordinates. We have simulated the Clouds as Plummer's models with masses and radii given in Table 3-2. Initial conditions of interaction are evolved with the Barnes-Hut *N*-body simulation code with the opening angle $\theta = 1.0$. The timestep is equal to $34.1 \cdot 10^3$ yr and the overall simulation covers $3.58 \cdot 10^9$ yr.

Milky Way		SMC		LMC		Evolution	
$M_{central}$	10.0	M_{SMC}	0.007	M_{LMC}	0.01	Timestep	0.0005
$R_{central}$	3.0	R_{SMC}	0.3	R_{LMC}	0.9	Steps	105,000
Q	1.5						
$N_{central}$	5,000	N_{SMC}	2,500	N_{LMC}	2,500		
Kuzmin		Plummer		Plummer			

Table 3-2: Model parameters of the MW, SMC and LMC interaction.

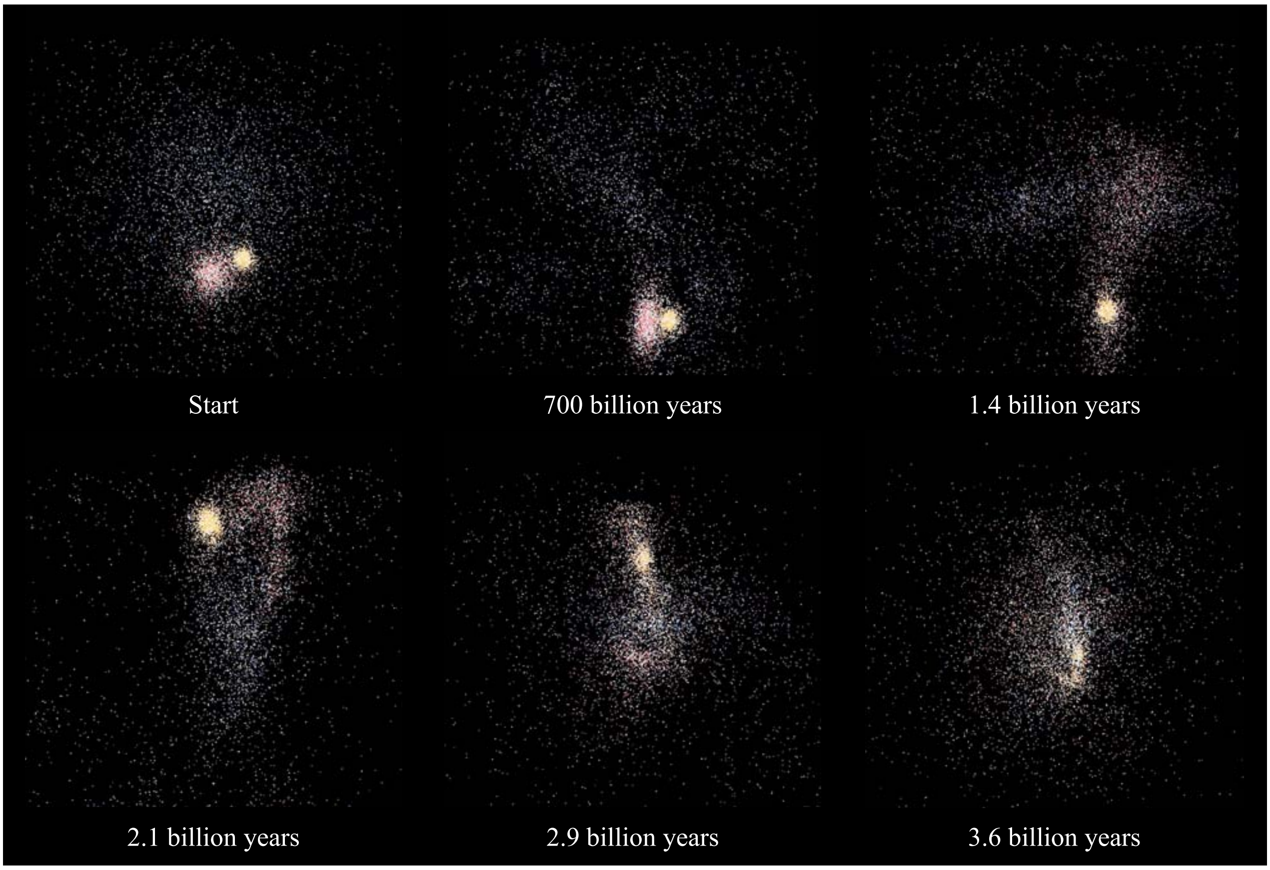

Figure 3–1: A time sequence for the Milky Way and the Small and Large Magellanic clouds merger in the *xy* plane evolved with the Barnes-Hut *N*-body algorithm.

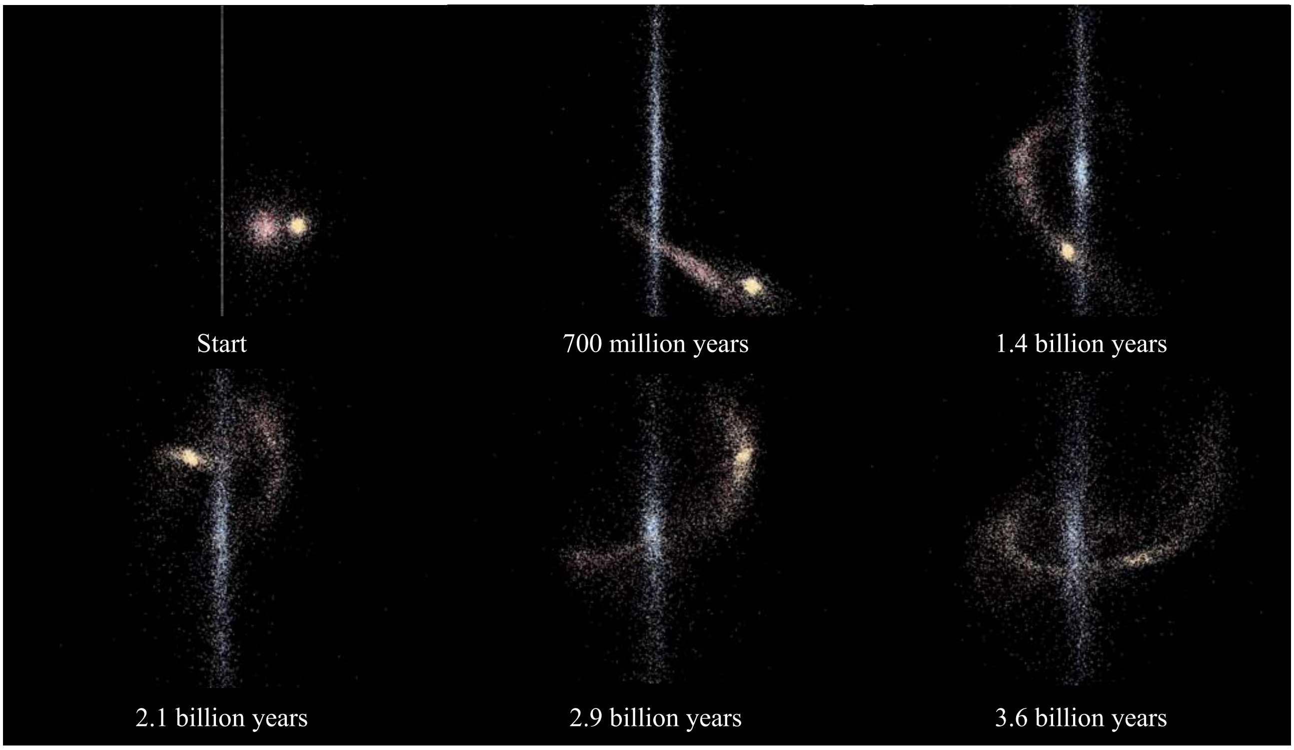

Figure 3–2: A time sequence for the Milky Way and the Small and Large Magellanic clouds merger in the *yz* plane evolved with the Barnes-Hut *N*-body algorithm. The formation of a Magellanic Stream-like feature can be seen.

4 Summary

What follows is a chapter-by-chapter summary of the main results of the thesis.

- In Chapter 1, we have described thesis objectives and methodology used in the thesis.
- In Chapter 2, we have shown that physics education is an important and crucial element for human society. Students should be more motivated by their teachers with less importance on learning and more emphasis on differentiation, individualization and self-teaching. It is for this purpose that the formation of self-teaching projects is suggested. Together with advancement in science and technology, an early connection of education and research should be made. Self-teaching educational-research projects created by specialists in their fields should be made freely available on the Internet as a service to society. A research method of education can develop student's abilities in a complex way. Computer models and simulations of nature's behavior are acknowledged as useful, providing connections between various fields of science education. A scheme incorporating these approaches is suggested in the "four-level educational architecture". Surely, education is a complex system and this concept may not be valid for every student.
- In Chapter 3, we have sketched our basic understanding of nature, laws of physics, models, simulations and confusion among them.
- In Chapter 4, we have shown how to simulate the effect of the gravitational field and of Newton's laws of motion to move the stars around. I described my implementation of Barnes-Hut algorithm for many-body simulation and novel geometry-based construction of the 3-dimensional Hilbert's curve. Simulation code works in four steps. First, a tree is constructed by space decomposition from a list of bodies that form the simulated system. Space is divided utilizing Hilbert's self-similar space-filling curve. Groups of close bodies are created. Second, centers of mass of individual nodes are computed. Third, accelerations are computed with the Barnes-Hut algorithm. Fourth, new positions and velocities are computed. Thanks to this algorithm, all simulations will be fully self-consistent, i.e. no rigid potentials will be employed.
- In Chapter 5, we have shown how to create a computer model of a galaxy in order to study galaxy dynamics. We found that the construction of galaxy in a controllable way is difficult. Due to immense complexity, all models are very artificial in comparison to real galaxies. In spite of that, the initial density distribution function of models are in good agreement with observations of real galaxies. The galaxy models created were single or multicomponent systems in stable dynamical equilibrium.

  Initial conditions were generated as follows. Specifying the mass density distribution function, we first calculate the model's cumulative mass distribution function and corresponding gravitational potential. Then the mass density distribution function is expressed as a function of gravitational potential. The phase-space distribution function is calculated on the fly using a numerical formulation of Eddington's formula. Once the phase-space distribution function has been calculated, one can start to randomly sample particles from the distribution function. If the use of another mass density profile is requested, all that is necessary, is to override a virtual function "rho" according to the chosen mass density profile. Through this approach, many kinds of models may be constructed. Models created in this way are quickly getting into equilibrium.

We created realizations of an elliptical galaxy from various spherical models. The spherical models were in equilibrium from the beginning. We have created disk models that showed continuous evolution. We saw that dynamically cold disk without a dark halo spontaneously formed features resembling galactic bar and spiral arms. It has been shown that a self-gravitating disk system is unstable unless a certain velocity dispersion and dark halo were included. All models were evolved for more than 1 billion years and movies from all computations were produced.

- In Chapter 6, we have demonstrated how to study galaxy collisions and mergers with computer simulations. Interacting galaxies are very complex and highly dynamic systems. With modest computational resources, we performed computer simulations of galaxy interactions that are in excellent agreement with observations. These simulations provide an accurate and entertaining insight into galaxy collisions and mergers.

  However, model results were not without their shortcomings. Our aim was not to study interactions in detail, but to show how such study can be done with all details provided. We studied the evolution of spherical galaxy interactions, minor and major mergers, and galaxy harassment.

  We simulated the evolution of the Milky Way galaxy, the Large and the Small Magellanic Clouds and all 19 known satellite galaxies of the Milky Way. We have simulated the future evolution of the Local Group in the collision of two disk galaxies representing the Andromeda galaxy (M31) and the Milky Way galaxy. Models were evolved for up to 8.1 billion years and movies from all computations were produced.

- In Chapter 7, we have shown how to prepare our simulation for the alternative gravity model. We have learned that the simulation of a galaxy in Modified Newtonian Dynamics (MOND) theory can be performed with at least the same result as the simulation in Newton's theoretical framework. Cosmological large-scale dark matter computer simulations performed by other authors agree with the observations, while the results on galaxy scales are inconsistent. These simulations with dark matter may miss some important small scale physics of both baryonic and non-baryonic matter that is not resolved with a current resolution of cosmological simulations and computer models, while the standard model can be accurate.

  One should be cautious, however, as the theory is stretched and adapted to fit the evidence, or facts are carefully selected to fit the theory. We learned from the history of physics that models of nature usually comprehended a lot of things accurately, but also usually missed important big ones. Mordehai Milgrom and others has done interesting work that healthy competes with dark matter theory. In any case, even if MOND should be revealed as an incorrect theory, it serves as a good exercise for galaxy modeling. We should keep in mind that "laws of physics" are not an accurate description of nature.

- In Chapter 8, we have presented the main features of simulation programs and how to use them. I developed several software tools for this thesis that are available publicly to the community. GENICS (Generator of Initial Conditions) and AMON-2 (Astronomical Modeling with *N*-bodies) contain together over 9,000 lines of C++ source codes. DIGALEX (Digital Galaxy Explorer) contains over 5,500 lines of C++ source codes. All of the source code of software is available at http://www.kof.zcu.cz/st/dis/schwarzmeier/ or on the companion Digital Versatile Disk (DVD), and is released under the GNU General Public License (GPL).

  I have created 70 animations that show simulated *N*-body systems described in the thesis. These animations are also available on mentioned internet website and on the companion DVD. I invite you to visit this website and explore all of these animations.

Shortened version of this thesis was presented at the conference "Moderní trendy v přípravě učitelů fyziky 3", Srní, Czech Republic, April 2007 and was accepted for publication in conference proceedings (Rauner, 2007). Parts were presented on two monthly meetings of our department and on the annual meeting of Ph.D. students of "Theory of Education in Physics".

4.1 Conclusions and future prospects

For the first time, a complete educational description of computer simulations of galaxy dynamics, from initial conditions generation to visualization is described in detail. It was framed into the self-teaching educational-research project. All parts of the thesis (both printed and electronic) are available for all interested on the internet website of the Department of General Physics.

The understanding of galaxy formation, evolution and interaction is obscured with complexity and uncertainty in the modeling of physical phenomena involved in galaxies. Future improvements of models should come with additional physics, and more of such self-teaching educational-research projects should be created and made publicly available.

ORIGINAL ABSTRACT OF THE Ph.D. THESIS

This work describes the self-teaching educational-research project involving many-body computer simulations with the objective of studying galaxy dynamics. This self-teaching project guides a student through numerical models and computer simulations of galaxy dynamics in detail. It shows the numerical construction of near-equilibrium galaxy models and how these artificial galaxies are evolved. Evolution is based on the Barnes-Hut algorithm and space division with a three-dimensional Hilbert's curve generated by a geometry-based technique. The educational-research part of this project shows how to simulate the evolution of the Milky Way galaxy, the Large and Small Magellanic Clouds and all of the 19 known satellite galaxies of the Milky Way, including recently discovered ones. A future evolution of the Local Group is simulated in the collision of two disk galaxies representing Andromeda galaxy (M31) and the Milky Way galaxy; Galaxy harassment is also briefly explored. Modified Newtonian Dynamics simulation as a possible rival of dark matter is described. Models were evolved for up to 8.1 billion years.

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