Chaotic Dynamics in N-body systems

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Future Directions

Several directions in the field of research of N-body systems and simulations are discussed, where further improvement is necessary. The first one is speed of N-body simulations in order to be able to handle large systems such as globular clusters. Especially the presence of binaries causes a major slow down. The second direction is precision, which is crucial when simulating systems including millisecond pulsars for example. Through high precision observations and simulations we can test theories of gravity to many decimal places. Finally, a better understanding of the quasi-ergodic property of gravity and the growth of perturbations will provide clues for designing new N-body methods and a more fundamental understanding of gravity and the evolution of dynamical systems.

7.1 SPEED

The first N-body simulations in the 1960s calculated the orbits of a few dozen stars (von Hoerner, 1960; Aarseth, 1963; **?**). Each decade later, this number increased by an order of magnitude, due to advances in computer hardware (**?**). The first star by star simulation of a rich globular cluster, with nearly half a million stars, has been completed recently (**?**), and now we are on the brink of the first such simulations with a million bodies (**?**). The comparison between a million-body star cluster simulation and observations of globular clusters, will involve less assumptions than comparing with simulations of a smaller number of bodies. For example, the relaxation time of a cluster depends on the number of bodies, and also rare events, such as collisions between stars or the fraction of exotic objects in the cluster, such as pulsars and black holes, depend on the number of bodies in the system.

The development of N-body methods is still an ongoing process, since there are certain types of configurations that are still hard to simulate efficiently. For example, star clusters are born with a fraction of primordial binary stars (**?**). The ratio between the crossing time of the cluster and the orbital period of a binary can be as high as six orders of magnitude. Integrating these systems directly is very computationally expensive. Approximation schemes, such as replacement by a center of mass body or nearest-neighbour methods (Aarseth, 2003), have to be implemented to be able to integrate these systems at all. Handling binary and higher-order systems in star clusters is challenging and new methods have to be constructed to improve the performance, while maintaining sufficient accuracy..

7.2 PRECISION

Some dynamical systems can be observed very precisely. The orbit of Halley's Comet for example, is known to about six decimal places (**?**). Since the comet is relatively nearby, it was possible to sent a spacecraft in 1986 to explore the comet from up close. Another example is that of a system including a pulsar. Pulsars are fast rotating neutron stars from which we receive a signal twice every rotational period (**?**). The timing of these signals can be precise up to 15 decimal places, making them one of the most accurate clocks in nature (**?**). Variations in these timing measurements are caused by internal processes in the pulsar, but can also hold information about its dynamical environment.

These precise systems need to be modelled using both accurate physical models and integration techniques. Starting with Newtonian dynamics and a precise N-body integrator such as Brutus (**?**), the simulation data can be compared to the observations. If there are residuals left in the comparison, higher-order effects have to be taken into account to solve for them. These could be relativistic effects in systems with high masses or large velocities, finite size effects if objects approach each other closely, or simply reducing the effect of numerical errors. Through studies such as these, and applying them to systems of extreme gravity including pulsars or black holes, we can test theories of gravity to high precision.

7.3 RELIABILITY AND CHAOS

In this thesis, we investigated the reliability of numerical integration for a subset of three-body systems (**?**). The fact that we confirm the preservation of statistics under divergence of solutions, does not guarantee that other N–body systems do the same (**?**). Starting with a four-body system, one body can escape, leaving behind a three-body system. The configuration of this three-body system however, is probably different than the three-body systems we investigated. Therefore, in principle, every value of N should be tested independently.

Such studies can only show whether the results from N-body simulations are correct in a statistical sense. They do not however, explain why this is the case. More theoretical work is needed to understand the quasi-ergodic behaviour of gravity (**?**). For what type of systems does it hold, and are there systems for which it breaks down? This last case would be particularly interesting, because results of simulations of such systems would have to be reconsidered.

Some light in this largely unexplored field of research, might be shed by investigating a related topic on the dynamical stability and growth of perturbations in dynamical systems. In this thesis, we started by constructing a model for the growth of perturbations, explaining both regular and chaotic behaviour in the orbit of Halley's Comet (Boekholt et al., In prep.). This study should be expanded by including more general orbits and configurations. By understanding how perturbations or errors propagate through a dynamical system, we will also be in a better position to design new N-body methods, which are adapted to our understanding of error growth. Apart from improving our simulation methods, it will also provide us with a more fundamental understanding of the way gravity works, which will lead to a better understanding of the evolution of dynamical systems in the universe

The field of N-body methods and simulations has become increasingly important for astronomers. It has improved our understanding of dynamical systems, and it will continue to make a significant impact in astronomy. In this age of big data, where many large surveys, such as the Gaia mission[1], will acquire more complex and deeper observations, more sophisticated and realistic modelling is required, in order to interpret the observations from a dynamical point of view (**?**).

[1]http://sci.esa.int/gaia/