Preface

The aim of this book is twofold: to provide an introduction for newcomers to state of the art computer simulation techniques in space plasma physics and an overview of current developments. Computer simulation has reached a stage where it can be a highly useful tool for guiding theory and for making predictions of space plasma phenomena, ranging from microscopic to global scales.

The various articles are arranged, as much as possible, according to the underlying simulation technique, starting with the technique that makes the least number of assumptions: a fully kinetic approach which solves the coupled set of Maxwell's equations for the electromagnetic field and the equations of motion for a very large number of charged particles (electrons and ions) in this field. Clearly, this is also the computationally most demanding model. Therefore, even with present day high performance computers, it is the most restrictive in terms of the space and time domain and the range of particle parameters that can be covered by the simulation experiments.

It still makes sense, therefore, to also use models, which due to their simplifying assumptions, seem less realistic, although the effect of these assumptions on the outcome of the simulation experiments needs to be carefully assessed. In fact, using a model which is not realistic in every respect may, instead of a limitation, even represent a particular strength of simulation. Such models allow isolating particular physical mechanisms, something which is often not possible with space observations or even with laboratory experiments, in view of their complexity. In this manner our theoretical understanding can be advanced.

One such simplification, often also employed in theoretical treatments, uses of the fact that plasma waves are often nearly electrostatic. Corresponding codes are not only simpler, because there is no need to compute magnetic field perturbations. They are also more efficient, because wave phase speeds that need to be resolved are generally much smaller than for electromagnetic waves. By comparing electrostatic and electromagnetic code results, one can easily assess the importance of electromagnetic effects in plasma dynamics.

Space plasmas, in contrast to laboratory devices, are very extended coupled systems. Boundary conditions, which a computation necessarily has to introduce, are thus always somewhat artificial. Using two- or even one-dimensional models allows minimizing this artifact in the remaining dimensions. Especially with one-dimensional models, however, careful analysis must ensure that they do not too much restrict interaction mechanisms, between particles and waves, for example.

Even the fully kinetic simulations by the particle in cell (PIC) simulation technique simplifies the computational task by concentrating on collective, long range electromagnetic fields, which dominate the dynamics of most space plasmas. This method of representing the plasma by finite size particles still leaves background statistical noise, with effects similar to particle collisions. It is reduced only as $N^{-\frac{1}{2}}$, as the number of such super particles increases. A method to more efficiently reduce the noise level is to split the particle distribution function, when this seems possible, into a fixed background f_0 and a perturbation δf and representing only the latter by simulation particles.

In a dusty plasma, however, the short range forces, which describe collisions, become important, at least between dust grains. The evaluation of these forces for N particles requires the summation of N^2 interactions. Moreover, dust grains are so much more massive than plasma ions and electrons, and hence move on vastly different time scales, which also largely prohibits using the same simulation technique as for the background plasma. One can, however, take advantage of this disparity in characteristic scales, by combining molecular dynamics simulation techniques for the dust grains with a description, obtained from linear kinetic theory, of the plasma as a dielectric which modifies the forces on dust grains.

A very significant reduction in computational cost arises if at least one particle species can reasonably be represented by a simple fluid model. In so called hybrid models, usually the electrons are represented in this way, whereas for the ions a fully kinetic description by particles is used. Situations in which, by contrast, electron kinetic effects dominate are also possible, of course.

The most significant reduction in computational cost arises if all particle species are represented by fluids, or even a single conducting fluid. In return, such magnetohydrodynamic models nowadays allow global simulations of the entire coupled solar wind-magnetospheric system. The ongoing challenge, as computer power increases, is to make the description of the plasma and the boundary conditions, especially the planetary boundary conditions, more complete. Predictions of space weather require as input, at another boundary, also realistic descriptions of solar activity.

Along with advances in computer hardware, advanced programming and numerical techniques, which make optimal use of this new computer power, such as massively parallel computations or codes with variable mesh size, are equally important. Finally, special attention must be paid to efficient techniques for analyzing and representing the massive amount of data, which simulations, three-dimensional computations especially, nowadays produce.

This book was inspired by the Sixth International School / Symposium for Space Plasma Simulation, held at Garching, Germany, in September 2001. Its invited tutorials and review lectures had the same aims. We therefore invited authors to contribute who, in a collective effort, would give a most coherent and reasonably complete picture of this diverse and rich field. To this end individual contributions were made available to all contributing authors during the preparation phase of this book, and authors were encouraged to freely exchange comments. In addition, each contribution was subject to a formal peer review process. We feel very fortunate to have found such highly qualified authors who, as a group, have indeed covered a huge range of topics, as the table of contents shows. Our thanks go to them, but also to the referees who helped to further improve the presentation.

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