Chapter 1

Introduction

The general subject of this dissertation is the numerical study of shock phenomena in magnetohydrodynamic (MHD) plasmas.

Shock phenomena in gases are common and can be experienced in everyday life — a well-known example is the sonic boom caused by supersonic airplanes. Shocks are discontinuous jumps in macroscopic quantities like velocity, pressure and density.

A plasma is an *ionized* gas, and exhibits more complex behavior than a neutral gas, because of electromagnetic effects. Electric and magnetic fields exert anisotropic forces on the *charged* particles which constitute a plasma, and the charge and the current carried by the particles influence the electric and magnetic fields. Like in neutral gases, shocks can form in plasmas, but plasma shock phenomena exhibit a richer complexity and variety than their neutral gas counterparts. Shock phenomena in plasmas continue to be investigated today because the basic physical processes are not fully understood.

Most of the matter in the solar system is in the plasma state, and plasma shocks are ubiquitous in the solar system. Bow shocks are formed in front of planets and comets by the supersonic solar wind. Fast ejections of mass from the solar corona induce leading shock fronts. These ejecta with associated shock fronts may travel in the direction of the earth as magnetic clouds which can cause severe disruptions of the earth's magnetic environment. Plasma shock phenomena also play an important role in other astrophysical plasmas and in laboratory plasmas.

Many scientific spacecraft have been launched in the last decades to collect observational data on solar system plasmas. Important examples include the Ulysses mission which studies planets and the interplanetary medium, the Solar and Heliospheric Observatory (SOHO) which is dedicated to the study of the sun, and the CLUSTER mission which will be launched by mid-2000 to observe the earth's bow shock and magnetosphere. These spacecraft provide a wealth of observational data on shock phenomena in solar system plasmas. Those observations reveal many unexplained features, and an increased theoretical understanding of plasma shock phenomena is necessary for the interpretation of the observations.

There exists a hierarchy of theoretical models that describe plasma motions at different levels of complexity. The MHD approximation describes a plasma as a continuous electrically conducting fluid. This approach does not take into account microscopic plasma processes which may be important for the explanation of some physical phenomena, but it provides a consistent and tractable description of plasma flows with shocks on macroscopic scales. The MHD description of a plasma is adopted in this dissertation.

The results to be presented in this dissertation aim at contributing to the general theory of shock phenomena in MHD plasmas. In particular, the influence of intrinsically magnetic effects on bow shock flow topology is studied via numerical simulations of MHD bow shock flows in two and three spatial dimensions. The problem is studied in the classical setting of stationary bow shock flows around perfectly conducting rigid obstacles — cylinders, spheres and paraboloids. This abstract context allows to concentrate on the basic physical effects and to state the results in all their generality. At the same time, real space physics applications — for example the flow of the supersonic solar wind over an unmagnetized planet — remain conceptually close to this abstract setting, so it is not difficult to keep the practical importance of these abstract basic flow problems in mind.

The following specific subjects are addressed in this dissertation.

First, it is shown that when the flow upstream from the obstacle is magnetically dominated, stationary MHD bow shock flows exhibit a surprisingly complex topology involving multiple interacting shocks with segments of various MHD shock types. We call the upstream flow magnetically dominated — as opposed to pressure-dominated — when magnetic forces dominate over thermal and dynamic pressure effects such that the intrinsically magnetic phenomenon of the *switch-on shock* is encountered on the bow shock front. The resulting bow shock flow and bow shock topology are also called magnetically dominated. The complex magnetically dominated bow shock topology was not previously known, but can be understood in terms of the geometrical properties of MHD waves and shocks. This result adds to our general understanding of the phenomenology of MHD bow shock flows. It shows that there exist two basic topologies for MHD bow shock flows. For pressure-dominated upstream flows the traditional single-front topology arises which is well-known from hydrodynamic bow shock flows. Magnetically dominated MHD bow shock flows exhibit the new complex multiple-front topology.

Second, an in-depth analysis of the simulation results is given using analytical properties of the MHD equations, which confirms the presence of peculiar nonlinear MHD wave phenomena — in particular *intermediate shocks* and *compound shocks* — in the two-dimensional (2D) and three-dimensional (3D) simulation results. In recent years there has been much debate about the existence of these types of waves. Until recently they have mainly been studied in one-dimensional (1D) systems. Our simulation results seem to be the first clear confirmation of their existence in 2D and 3D.

Third, it is described how a robust and accurate numerical code has been developed for simulation of MHD flows with shocks. The PAR-MA (PARallel MAgnetohydrodynamics) code solves the mathematically well-behaved MHD equations on massively parallel computers using advanced numerical techniques. The numerical scheme used derives from state-of-the-art methods used in the field of Computational Fluid Dynamics. It is shown through careful validation studies that the extended numerical scheme produces valid results. It seems that the use of advanced numerical techniques and fast parallel computers was essential for obtaining the new results on magnetic effects in 2D and 3D MHD bow shock flows.

Fourth, it is shown how the simulation results are relevant for bow shocks in the solar system with magnetically dominated upstream flows. Two examples are discussed, namely shocks induced by fast coronal mass ejections (CMEs) propagating out of the solar corona, and the bow shock formed by the interaction of the sometimes magnetically dominated solar wind with the earth's magnetosphere.

Outline of the dissertation

Chapter 2 serves to introduce the general subject of this dissertation in an intuitive way. We give an overview of the results on MHD bow shock flows which are presented throughout the dissertation, and we sketch the broader context of the thesis research.

In Chapter 3 we describe analytical properties of the ideal MHD system. We present a derivation of the characteristic theory of steady MHD flow in 2D. We discuss the MHD Rankine-Hugoniot jump conditions, the non-convexity of the MHD flux function, and the properties of compound shocks.

In Chapter 4 we describe the PAR-MA finite volume numerical code that was developed to perform MHD flow calculations with shocks. We describe the spatial and temporal discretization, the control of the $\nabla \cdot \vec{B}$ constraint through a source term, and the implementation on parallel computers.

Chapter 5 contains a careful validation study of the numerical technique based on the simulation and characteristic analysis of 2D model flows with shocks.

In Chapter 6 we treat 2D symmetrical MHD bow shock flows around a cylinder with the magnetic field aligned to the plasma flow. A parameter study shows that intrinsically magnetic effects substantially change the topology of bow shocks for magnetically dominated upstream flows. A complex topology with a 'dimple' and secondary shock fronts results. We perform a detailed analysis of all the discontinuities present in these flows, and prove the presence of intermediate and compound shocks using characteristic theory.

In Chapter 7 we study 3D MHD bow shock flows over a sphere. A previously unknown topology is obtained for 3D magnetically dominated bow shock flows, containing two consecutive interacting shock fronts with shock segments of fast, intermediate and slow type.

Chapter 8 discusses how the new results on bow shock topology for magnetically dominated upstream flows are relevant for two examples of bow shock flows in the solar system. We describe how observations of fast solar CMEs and observations of the earth's bow shock flow may show evidence of the complex bow shock topology which was discovered in our simulation results.

The topic of the existence of intermediate shocks is addressed in Chapter 9. We illustrate the main issues of the ongoing debate on the existence of intermediate shocks, and we show how our simulation results are relevant for this debate.

In Chapter 10 we formulate our conclusions and describe directions for future work.