# Collisionless Shocks in Space Plasmas

Shock waves are an important feature of solar system plasmas, from the solar corona out to the edge of the heliosphere. This engaging introduction to collisionless shocks in space plasmas presents a comprehensive review of the physics governing different types of shocks and processes of particle acceleration, from fundamental principles to current research. Motivated by observations of planetary bow shocks, interplanetary shocks and the solar wind termination shock, it emphasizes the physical theory underlying these shock waves. Readers will develop an understanding of the complex interplay between particle dynamics and the electric and magnetic fields that explains the observations of in situ spacecraft.

Written by renowned experts in the field, this up-to-date text is the ideal companion for both graduate students new to heliospheric physics and researchers in astrophysics who wish to apply the lessons of solar system shocks to different astrophysical environments.

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# COLLISIONLESS SHOCKS IN SPACE PLASMAS

## Structure and Accelerated Particles

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CAMBRIDGE UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9780521514590



First published 2015

Printed in the United Kingdom by TJ International Ltd. Padstow Cornwall

*A catalogue record for this publication is available from the British Library*

ISBN 978-0-521-51459-0 Hardback

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# Preface

The study of shock waves in collisionless plasmas has a long history of over 50 years. That of shock waves in gas dynamics has roots which go back to the foundations of applied mathematics in the twentieth century, the nature of hyperbolic systems of equations and the physics of blast waves. Much of this early work was associated with military research, and some of the earliest work on shock waves in plasmas started from a similar background. However, in the early 1960s it was in space that truly collisionless shocks were first observed. With the advent of high-resolution space observations a fundamental challenge came into being: how can nonlinear collective processes replace the action of particle collisions and lead to thin shock waves in a collisionless plasma? In other words: how do collisionless shocks work?

With the growing exploration of space and better understanding of the plasma physics of the heliosphere, the importance of shocks has become evident. Shocks are formed around the planets in the supersonic flow of the solar wind; they are formed ahead of the impulsive flows of coronal mass ejections, and at the steady interaction regions between solar wind with different speeds; the entire region of the solar wind is defined by an outer boundary, the solar wind termination shock, where the flow transitions to subsonic as it comes into balance with the interstellar medium. In parallel to our increasing understanding of solar system shocks, it has become obvious that shock waves will arise in many other astrophysical systems, and that often the physics will be dominated by collisionless processes. A widely cited example is the shock wave driven by a supernova remnant; such shocks are understood to be vital for explaining the majority of cosmic ray acceleration.

In writing this book we had three aims in sight. We felt there was a need for a graduate level textbook that brought together the physics of collisionless shocks as found in the heliosphere, with an emphasis on the theoretical underlying physics of shock waves in plasmas. And it turns out that there are, depending on the shock parameters, several answers to the question: ‘How do collisionless shocks work?’

So, secondly, we wanted to present a review of the different types of shock structure, and how that structure is determined by the different basic processes which provide collisionless dissipation. Finally, particle acceleration is a fundamental property of collisionless shocks, and we wished to show how acceleration processes and shock structure are intimately related.

Our perspective is primarily theoretical and simulation-based, but motivated by observations. Therefore we include discussions of the most important observational results in order to demonstrate the main characteristics of heliospheric shocks. Simply because of the wealth of available data, in terms of detail and parameter coverage, these discussions are dominated by results from the Earth's bow shock. In many ways the Earth's bow shock can be taken as an exemplar of collisionless shocks in space plasmas. The drawback of this approach is that it underplays the variety of solar system shocks – from the bow shock of Mercury to that of Uranus, and from shocks in front of coronal mass ejections to the solar wind termination shock.

In writing a book such as this there are hard choices about what to put in and what to leave out. Our intention has been to describe a body of work that has a robust status, and we know that in making our selections we have left out much interesting work. But we hope that we provide a framework for further advanced study where all the contradictions and loose ends inherent in active research might be appreciated. For this reason we have intentionally avoided discussing contemporary work, which is best left to review articles. An exception is some of the work on the heliospheric termination shock, where recent advances have led to a re-evaluation of our state of knowledge. We are aware that with the continual improvement of computers some simulations which we describe will eventually be regarded as merely historic. However, we hope that we have selected those that will, nevertheless, retain their relevance. There are also some areas where we have decided that, in order to make writing the book a finite task, certain topics must be left out or not given a full discussion. For example, the foreshock is only discussed as it is directly relevant to the shock structure. Over time a myriad of instabilities has been invoked when studying collisionless shocks, but we have selected only those which we feel are most important, and extracted their relevant properties. We have also shamelessly concentrated on fast-mode shock waves, and said little about slow-mode shocks. There are few published observations and similarly few theoretical and simulational papers, which probably reflects the importance of slow shocks in the heliosphere, so we feel this subject is better dealt with by review articles.

Finally, we wish to acknowledge that our view of collisionless shocks rests on the work of many colleagues, and their generous sharing of ideas and results at workshops, conferences and in the literature. In particular we would like to thank the following individuals for helpful discussions concerning specific topics: D. Biskamp, J. Giacalone, P. Hellinger, R. A. Jokipii, B. Klecker, D. Krauss-Varban, S. Matsukiyo, M. A. Lee, G. Paschmann, P. Savoini, S. J. Schwartz, T. Terasawa and D. Winske. We would also like to thank P. W. Gingell and T. Sundberg for assistance with proofreading the manuscript.