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Solitary Waves in Dispersive Complex Media

Theory · Simulation · Applications

With 100 Figures

Springer

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Dedication

To our parents:

Yury G. Belashov, a distinguished physicist, and Lyudmila V. Belashova, an outstanding engineer

Vladimir N. Vladimirov and Galina I. Vladimirova, outstanding engineers and teachers

Preface

This book is devoted to one of the most interesting and rapidly developing areas of modern nonlinear physics and mathematics – theoretical, analytical and numerical, study of the structure and dynamics of one-dimensional as well as two- and three-dimensional solitons and nonlinear wave packets described by the Korteweg–de Vries (KdV), Kadomtsev–Petviashvili (KP), nonlinear Schrödinger (NLS) and derivative nonlinear Schrödinger (DNLS) classes of equations. Special attention is paid to generalizations (relevant to various complex physical media) of these equations, accounting for higher-order dispersion corrections, influence of dissipation, instabilities, and stochastic fluctuations of the wave fields.

We present here a coordinated approach to the theory, simulations, and applications of the nonlinear one-, two-, and three-dimensional solitary wave solutions. Overall, the content of the book is a systematic account of results not only already known in the literature, but also those of new original studies related to the theory of models allowing soliton solutions, and analyses of the stability and asymptotics of these solutions. We give significant consideration to numerical methods and results of numerical simulations of the structure and dynamics of solitons and nonlinear wave packets. Together with deep insights into the theory, applications to various branches of modern physics are considered, especially to plasma physics (such as space plasmas including ionospheric and magnetospheric processes), hydrodynamics, and atmosphere dynamics.

Presently, the theory of one-dimensional nonlinear equations of the classes considered by the authors is well developed, and the progress in studies of the structure and evolution of one-dimensional solitons and wave packets is obvious. This progress was especially fast after the discovery of hidden algebraic symmetries of the KdV, NLS, and other (integrable by the inverse scattering transform (IST) method) classes of one-dimensional evolution equations. However, as soon as generalizations of these classes on more complex cases are involved, especially in two and three dimensions, the corresponding systems are often not completely integrable in the generally accepted mathematical sense. Thus an analytic study can provide us, in the best case, with the mere answer on the stability of multidimensional wave solutions and their asymptotics, and, by analyzing the system's behavior in the phase space, can give us qualitative characteristics and classification of the solutions. The detailed study of the structure and dynamics of multidimensional nonlinear waves, not solvable analytically in the general case, thus demands development of proper high-precision and highly effective numerical methods of integration of the related nonlinear systems as well as numerous numerical simulations. This type of research is now mostly represented in uncoordinated journal and conference publications covering particular aspects of the problem, without providing a unified systematic approach.

There is another, in our view, important reason, and that was also one of the major incentives prompting us to write this book. Presently, despite a number of works on mathematical properties of solitons, there is practically no systematic monograph-type literature on the theory of multidimensional KP- and DNLS-class equations, and especially on their applications to various physical situations. Thus important general theoretical results often are not recalled in applied calculations of physical phenomena in various physical systems, leaving these classes of equations as well as their solutions as "exotic objects" for narrow specialists in particular subjects. As an example, we can mention effects related to dissipation, processes leading to developing instabilities and formation of complex turbulent structures, higher-order dispersion effects, influence on the evolution of wave packets of stochastic fluctuations of the wave field, etc. On the other hand, almost all of the above effects are intrinsic properties of nonlinear dispersive complex systems attracting wide attention presently.

We cannot pretend to provide an exhaustive account of all the aspects of the modern theory of "soliton equations" because of its continuing intensive development; however, we hope that the present book does help fill the existing gaps in the literature. Our book is practically the first time for monographic literature to discuss in detail such problems as structure, stability, and dynamics of the nonlinear wave solutions, especially those of KP- and DNLS-classes, consistently taking into account effects, important in the physics of real complex nonlinear media; we study problems of development of relevant classification of allowed solutions in the phase space and by characteristics of their asymptotics; we deeply consider the ideology and realization of new, including so called spectral, approaches to numerical integration of the related multidimensional nonlinear systems, differing from the known methods by their high efficiency and possibility to control evolution of the solutions and soliton interaction in its dynamics.

The spectrum of applications presented in this book is sufficiently wide. Together with well known examples associated with the evolution of hydrodynamic surface waves, ion-acoustic and magnetosonic plasma waves (for the latter we also discuss a number of new results related to the account of relativistic effects as well as the influence of dissipation, stochastic fluctuations of the wave field and higher-order dispersion corrections, which can lead to formation of essentially new types of solutions), we discuss for the first time applications to the analysis of the dynamics of nonlinear solitary internal gravity waves in the Earth's ionosphere, including those generated by fronts of solar terminator and the shadow of a solar eclipse; we investigate the action of Raleigh waves off a seismic source on the plasma dynamics of the ionosphere's F-layer; we study dynamics of multidimensional solitons in media with changing in space and time dispersion characteristics (in particular, we investigate the problem of the structure and deformations of two-dimensional solitons propagating on the surface of a shallow water with changing profile of the bottom). We hope that the considered applications together with analytical and numerical results presented in a consistent and invariant way will help the interested reader apply the corresponding methods to the solution of particular problems in his/her field of research.

We also note that content of this book is a result of generalization of our teaching experience in the development of courses on the theory and numerical modeling of the nonlinear wave dynamics for students at graduate and post-graduate levels. This strongly influenced the structure of the book; we also hope that the methodic selection and presentation of the content will allow to use this publication as a reference book not only for students but also for scientists in various fields of modern physics.

We thus address this publication to researchers working in the theory and numerical simulations of dispersive complex media in such fields as hydrodynamics, plasma physics, and aerodynamics. As a reference book, we expect the monograph to be useful to graduate and post-graduate students majoring in physics and mathematics, as well as to scientists interested in solitons and nonlinear waves in other nonlinear dispersive complex systems.

It is our pleasure to thank many people to whom we owe a great deal. Vasily Belashov is especially thankful to Vladimir Karpman for his stimulation and long term collaboration on many research topics, Vladimir Petviashvili for his kind attention to the research and discussions stimulated this book, as well as Oleg Pokhotelov, Yoshi-Hiko Ichikawa and Masashi Hayakawa for their permanent interest to this work, numerous useful discussions and support. Sergey Vladimirov thanks Vadim Tsytovich, a great mentor, from whom he has drawn much inspiration, as well as Lennart Stenflo and Ming Yu, his valued experts on nonlinear surface and plasma waves, for their influence, support, and close research collaboration over the years. We would also like to thank Yuri Kivshar for his continuing and stimulating interest to the topic.

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Kazan, Sydney, October 2004

V.Yu. Belashov
S.V. Vladimirov

Table of Contents