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R. Paul Drake

High-Energy-Density Physics

Fundamentals, Inertial Fusion, and Experimental Astrophysics

With 172 Figures

Springer

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Dedicated to Kent Estabrook

Preface

This book has two goals. One goal is to provide a means for those new to high-energy-density physics to gain a broad foundation from one text. The second goal is to provide a useful working reference for those in the field.

This book has at least four possible applications in an academic context. It can be used for training in high-energy-density physics, in support of the growing number of university and laboratory research groups working in this area. It also can be used by schools with an emphasis on ultrafast lasers, to provide some introduction to issues present in all laser–target experiments with high-power lasers, and with thorough coverage of the material in Chap. 11 on relativistic systems. In addition, it could be used by physics, applied physics, or engineering departments to provide in a single course an introduction to the basics of fluid mechanics and radiative transfer, with dramatic applications. Finally, it could be used by astrophysics departments for a similar purpose, with the parallel benefit of training the students in the similarities and differences between laboratory and astrophysical systems.

The notation in this text is deliberately sparse and when possible a given symbol has only one meaning. A definition of the symbols used is given in Appendix A. In various cases, additional subscripts are added to distinguish among cases of the same quantity, as for example in the use of ρ_1 and ρ_2 to distinguish the mass density in two different regions. With the goals of minimizing the total number of symbols and of using them uniquely, the text avoids various common usages. An example is the use of μ for the coefficient of viscosity, which is avoided, with the viscosity expressed always as the product or $\rho\nu$, where ν is the kinematic coefficient of viscosity.

Much of the homework throughout this text is only feasible using a computational mathematics program. The author prefers *Mathematica*, which has been an essential tool in the preparation of this text, but there are now and will be several such programs available. This departure from traditional norms reflects the emergence of such programs as effective tools. They should be part of the standard toolkit of all future scientists. This dramatically changes the meaning of "simple" solutions to problems. For example, an eighth-order polynomial equation is not necessarily difficult to deal with. Appendix B includes examples of *Mathematica* code for two of the issues discussed in the book, to help the reader get started.

A word on the use of units is in order. The metric system in a broad sense is the common language of science. But the world in general and high-energy-density systems, in particular, are not conveniently analyzed within any single standard subsystem of these units. Each of the SI system, the Gaussian cgs system, and other systems is the most convenient for certain problems, as are a few other specific units such as the electron Volt. This is why these systems exist. It is an *essential* tool for a practicing scientist to be able to readily convert between systems of units "on the fly". This is true because the existing literature is presented for the most part in convenient units, which working scientists use because they are convenient. But comparisons of one system to another are very important as checks on one's reasoning, and this often leads to the need to convert units. Thus, the author is an adamant opponent of the SI purists who would commit nothing to print that is not in SI units and an adamant advocate for defining one's units in all work one does. When feasible, the equations in this book are written in unit-independent form. When this is not possible, as for example with the Lorentz force, the units are specified and are usually in the Gaussian cgs system, which is the most convenient for most plasma applications. The units are also specified when practical equations are given. At least this was the author's intent. Please let him know where he failed. Finally, the appendix on units in Jackson's *Classical Electrodynamics* is an excellent reference on this subject.

Bibliographic references are sparse in most chapters of this text. Most of the references are to published books that address a certain topic in more detail than is feasible here. The journal literature is cited only when there are as yet no relevant books, and such citations often fail to reflect the scope of work in the journal literature. This was deliberate for several reasons. One of my goals has been to write a book that will prove useful for many years. The archival literature changes rapidly and the present era is one of very rapid advance in high-energy-density physics and in astrophysics. As a result, any references to the current literature will rapidly become dated. In addition, the era of immediate bibliographic database searches is here to stay, so future readers will readily be able to find up-to-date references in the archival literature of their time.

A second goal has been to present the material here with a common voice, because in the opinion of the author this is pedagogically most effective. A book that ties itself too closely to published literature can become disjointed. A third goal has been to show that this material is "simple", in the sense that a physicist would use. A rich panoply of phenomena evolves straightforwardly from what are at root a few and simple starting equations. In the spirit of Richard Feynman, one can understand a great deal without needing more than clear thinking. (Though one must add that a computational mathematics program helps a lot for some nonlinear problems.) The greatest departure from this goal has been in Chaps. 3 and 8, where to avoid very protracted discussions we have been forced to ask the reader to accept some details without much explanation.

Throughout this text, there are a number of figures showing the results of computer simulations, in order to display hydrodynamic and radiation hydrodynamic phenomena. Unless otherwise noted, these simulations were done using the HYADES computer code authored by Jon Larsen and available at this writing from Cascade Sciences Inc. A number of similar tools exist; they prove very useful for calculations to evaluate possible experiments and to identify the most important physical mechanisms in specific physical systems of interest.

Writing acknowledgments is rather daunting, given the many individuals who contribute to a project such as this. To those overlooked: remind me and I will at least buy you dinner. I must thank my family and my current research group for tolerating the time required for such a project. Dmitri Ryutov has been a source of inspiration, instruction, and encouragement, in addition to a vital collaborator, for a number of years, and also reviewed two chapters. Alexander Velikovich reviewed two chapters, made time for several delightful conversations, and significantly broadened my understanding of several issues. Harry Robey provided valuable insight into hydrodynamic instabilities and found an important error. Robert Kauffman and David Montgomery provided specific useful figures. Enam Chowdhury provided useful input and graciously allowed me to use some of his work. Michael DesJarlais, Warren Mori, Mordecai Rosen, Mark Hermann, James Knauer, Riccardo Betti, and Bedros Afeyan found time to comment on or discuss some of the material. Farhat Beg and William Kruer taught from the draft text. Ralph Schneider was a source of enduring encouragement.

The students in the lectures at Michigan in 2003 and 2005 and the 28 attendees of the summer school in 2004, though too numerous to list, helped identify errors and provided opportunities to improve the text. My own current graduate students Amy Reighard, Carolyn Kuranz, Eric Harding, and Tony Visco suffered through working with the draft, even while providing continuing motivation. Korbie Dannenberg, in addition to having done some of the work reflected in examples herein, kept my group moving forward when I was off writing. Jan Beltran provided a wide range of administrative assistance with the summer school and with the book, all of which I greatly appreciate. Of course, the responsibility for the errors in the text rests solely with me.

Beyond this specific group, I have enjoyed collaborations with a large community of scientists, engineers, and technicians during the past 20-plus years. A few of the key individuals not mentioned above are Dave Arnett, Jim Asay, Hector Baldis, Steve Batha, Bruno Bauer, Serge Bouquet, Jim Carroll, John DeGroot, Kent Estabrook, Adam Frank, Gail Glendinning, Martin Goldman, Tudor Johnston, Jave Kane, Paul Keiter, Alexei Khokhlov, Marcus

Knudson, Barbara Lasinski, Sergey Lebedev, Dick McCray, Tom Mehlhorn, Aaron Miles, Steve Obenschain, Ted Perry, Diana Schroen, Wolf Seka, Bob Turner, David Villeneuve, Russell Wallace, Bob Watt, James Weaver, and Ed Williams. There are many others. I also appreciate the positive interactions and encouragement from my editor at Springer, Dr. Chris Caron.

I love to work in coffee shops and was fortunate that my local favorite, Espresso Royale, opened a branch on Plymouth Road near my home early during this project. I did a lot of writing, editing, and deriving at their tables. To Sarah and all the staff who have worked there, thanks for the hospitality.

Finally, this book would not exist without two people. E. Michael Campbell talked me into entering this field when it had troubled times, supported doing the science needed to make inertial fusion succeed, and helped me move on when the time came for that. Bruce A. Remington talked me into jumping into the astrophysical applications of high-energy-density tools when this was a new idea and has continued to be a valuable collaborator since that time. I thank them both.

Ann Arbor, Michigan
December 2005

R. Paul Drake

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