An Introduction to Modern Astrophysics

Second Edition

An Introduction to Modern Astrophysics is a comprehensive, well-organized and engaging text covering every major area of modern astrophysics, from the solar system and stellar astronomy to galactic and extragalactic astrophysics, and cosmology. Designed to provide students with a working knowledge of modern astrophysics, this textbook is suitable for astronomy and physics majors who have had a first-year introductory physics course with calculus.

Featuring a brief summary of the main scientific discoveries that have led to our current understanding of the universe; worked examples to facilitate the understanding of the concepts presented in the book; end-of-chapter problems to practice the skills acquired; and computational exercises to numerically model astronomical systems, the second edition of *An Introduction to Modern Astrophysics* is the go-to textbook for learning the core astrophysics curriculum as well as the many advances in the field.

Bradley W. Carroll received his B.A. in Mathematics and a Secondary Teaching Credential from the University of California, Irvine, his M.S. in Physics from the University of Colorado, Boulder, and his Ph.D. in Astrophysics from the University of Colorado, Boulder. He then accepted a postdoc with Hugh Van Horn at the University of Rochester and, four years later, accepted a position in the Physics Department at Weber State University, where he served as the Physics Department chair for ten years. He retired in 2015 after 30 years at Weber. During this time, he was awarded the Lowe Innovative Teaching Award and named a WSU Brady Presidential Distinguished Professor. He is an emeritus member of the American Astronomical Society.

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CAMBRIDGE
UNIVERSITY PRESS

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University Printing House, Cambridge CB2 8BS, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

4843/24, 2nd Floor, Ansari Road, Daryaganj, Delhi – 110002, India

79 Anson Road, #06–04/06, Singapore 079906

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/9781108422161
DOI: 10.1017/9781108380980

This book was previously published by Pearson Education, Inc. 2007

Reissued by Cambridge University Press 2017

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

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

Additional resources for this publication at www.cambridge.org/astrophysics

ISBN 978-1-108-42216-1 Hardback

For Lynn,
and
Candy, Michael, and Megan
with love

Cambridge University Press
978-1-108-42216-1 — An Introduction to Modern Astrophysics
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Preface

Since the first edition of *An Introduction to Modern Astrophysics* and its abbreviated companion text, *An Introduction to Modern Stellar Astrophysics*, first appeared in 1996, there has been an incredible explosion in our knowledge of the heavens. It was just two months before the printing of the first editions that Michel Mayor and Didier Queloz announced the discovery of an extrasolar planet around 51 Pegasi, the first planet found orbiting a main-sequence star. In the next eleven years, the number of known extrasolar planets has grown to over 193. Not only do these discoveries shed new light on how stars and planetary systems form, but they also inform us about formation and planetary evolution in our own Solar System.

In addition, within the past decade important discoveries have been made of objects, within our Solar System but beyond Pluto, that are similar in size to that diminutive planet. In fact, one of the newly discovered Kuiper belt objects, currently referred to as 2003 UB313 (until the International Astronomical Union makes an official determination), appears to be larger than Pluto, challenging our definition of what a planet is and how many planets our Solar System is home to.

Explorations by robotic spacecraft and landers throughout our Solar System have also yielded a tremendous amount of new information about our celestial neighborhood. The armada of orbiters, along with the remarkable rovers, Spirit and Opportunity, have confirmed that liquid water has existed on the surface of Mars in the past. We have also had robotic emissaries visit Jupiter and Saturn, touch down on the surfaces of Titan and asteroids, crash into cometary nuclei, and even return cometary dust to Earth.

Missions such as Swift have enabled us to close in on the solutions to the mysterious gamma-ray bursts that were such an enigma at the time *An Introduction to Modern Astrophysics* first appeared. We now know that one class of gamma-ray bursts is associated with core-collapse supernovae and that the other class is probably associated with the merger of two neutron stars, or a neutron star and a black hole, in a binary system.

Remarkably precise observations of the center of our Milky Way Galaxy and other galaxies, since the publication of the first editions, have revealed that a great many, perhaps most, spiral and large elliptical galaxies are home to one or more supermassive black holes at their centers. It also appears likely that galactic mergers help to grow these monsters in their centers. Furthermore, it now seems almost certain that supermassive black holes are the central engines responsible for the exotic and remarkably energetic phenomena associated with radio galaxies, Seyfert galaxies, blazars, and quasars.

The past decade has also witnessed the startling discovery that the expansion of the universe is not slowing down but, rather, is actually accelerating! This remarkable observation suggests that we currently live in a dark-energy-dominated universe, in which Einstein's cosmological constant (once considered his "greatest blunder") plays an important role in our understanding of cosmology. Dark energy was not even imagined in cosmological models at the time the first editions were published.

Indeed, since the publication of the first editions, cosmology has entered into a new era of precision measurements. With the release of the remarkable data obtained by the Wilkinson Microwave Anisotropy Probe (WMAP), previously large uncertainties in the age of the universe have been reduced to less than 2% (13.7 ± 0.2 Gyr). At the same time, stellar evolution theory and observations have led to the determination that the ages of the oldest globular clusters are in full agreement with the upper limit of the age of the universe.

We opened the preface to the first editions with the sentence "There has never been a more exciting time to study modern astrophysics"; this has certainly been borne out in the tremendous advances that have occurred over the past decade. It is also clear that this incredible decade of discovery is only a prelude to further advances to come. Joining the Hubble Space Telescope in its high-resolution study of the heavens have been the Chandra X-ray Observatory and the Spitzer Infrared Space Telescope. From the ground, 8-m and larger telescopes have also joined the search for new information about our remarkable universe. Tremendously ambitious sky surveys have generated a previously unimagined wealth of data that provide critically important statistical data sets; the Sloan Digital Sky Survey, the Two-Micron All Sky Survey, the 2dF redshift survey, the Hubble Deep Fields and Ultradeep Fields, and others have become indispensable tools for hosts of studies. We also anticipate the first observations from new observatories and spacecraft, including the high-altitude (5000 m) Atacama Large Millimeter Array and high-precision astrometric missions such as Gaia and SIM PlanetQuest. Of course, studies of our own Solar System also continue; just the day before this preface was written, the Mars Reconnaissance Orbiter entered orbit around the red planet.

When the first editions were written, even the World Wide Web was in its infancy. Today it is hard to imagine a world in which virtually any information you might want is only a search engine and a mouse click away. With enormous data sets available online, along with fully searchable journal and preprint archives, the ability to access critical information very rapidly has been truly revolutionary.

Needless to say, a second edition of BOB (the "Big Orange Book," as *An Introduction to Modern Astrophysics* has come to be known by many students) and its associated text is long overdue. In addition to an abbreviated version focusing on stellar astrophysics (*An Introduction to Modern Stellar Astrophysics*), a second abbreviated version (*An Introduction to Modern Galactic Astrophysics and Cosmology*) is being published. We are confident that BOB and its smaller siblings will serve the needs of a range of introductory astrophysics courses and that they will instill some of the excitement felt by the authors and hosts of astronomers and astrophysicists worldwide.

We have switched from cgs to SI units in the second edition. Although we are personally more comfortable quoting luminosities in ergs s^{-1} rather than watts, our students are not. We do not want students to feel exasperated by a new system of units during their first encounter with the concepts of modern astrophysics. However, we have retained the natural units of parsecs and solar units ($M_\odot$ and $L_\odot$) because they provide a comparative context for numerical values. An appendix of unit conversions (see back endpapers) is included for those who delve into the professional literature and discover the world of angstroms, ergs, and esu.

Our goal in writing these texts was to open the entire field of modern astrophysics to you by using only the basic tools of physics. Nothing is more satisfying than appreciating the drama of the universe through an understanding of its underlying physical principles. The advantages of a mathematical approach to understanding the heavenly spectacle were obvious to Plato, as manifested in his *Epinomis*:

> Are you unaware that the true astronomer must be a person of great wisdom? Hence there will be a need for several sciences. The first and most important is that which treats of pure numbers. To those who pursue their studies in the proper way, all geometric constructions, all systems of numbers, all duly constituted melodic progressions, the single ordered scheme of all celestial revolutions should disclose themselves. And, believe me, no one will ever behold that spectacle without the studies we have described, and so be able to boast that they have won it by an easy route.

Now, 24 centuries later, the application of a little physics and mathematics still leads to deep insights.

These texts were also born of the frustration we encountered while teaching our junior-level astrophysics course. Most of the available astronomy texts seemed more descriptive than mathematical. Students who were learning about Schrödinger's equation, partition functions, and multipole expansions in other courses felt handicapped because their astrophysics text did not take advantage of their physics background. It seemed a double shame to us because a course in astrophysics offers students the unique opportunity of actually using the physics they have learned to appreciate many of astronomy's fascinating phenomena. Furthermore, as a discipline, astrophysics draws on virtually every aspect of physics. Thus astrophysics gives students the chance to review and extend their knowledge.

Anyone who has had an introductory calculus-based physics course is ready to understand nearly all the major concepts of modern astrophysics. The amount of modern physics covered in such a course varies widely, so we have included a chapter on the theory of special relativity and one on quantum physics which will provide the necessary background in these areas. Everything else in the text is self-contained and generously cross-referenced, so you will not lose sight of the chain of reasoning that leads to some of the most astounding ideas in all of science.[1]

Although we have attempted to be fairly rigorous, we have tended to favor the sort of back-of-the-envelope calculation that uses a simple model of the system being studied. The payoff-to-effort ratio is so high, yielding 80% of the understanding for 20% of the effort, that these quick calculations should be a part of every astrophysicist's toolkit. In fact, while writing this book we were constantly surprised by the number of phenomena that could be described in this way. Above all, we have tried to be honest with you; we remained determined not to simplify the material beyond recognition. Stellar interiors,

[1] Footnotes are used when we don't want to interrupt the main flow of a paragraph.

stellar atmospheres, general relativity, and cosmology—all are described with a depth that is more satisfying than mere hand-waving description.

Computational astrophysics is today as fundamental to the advance in our understanding of astronomy as observation and traditional theory, and so we have developed numerous computer problems, as well as several complete codes, that are integrated with the text material. You can calculate your own planetary orbits, compute observed features of binary star systems, make your own models of stars, and reproduce the gravitational interactions between galaxies. These codes favor simplicity over sophistication for pedagogical reasons; you can easily expand on the conceptually transparent codes that we have provided. Astrophysicists have traditionally led the way in large-scale computation and visualization, and we have tried to provide a gentle introduction to this blend of science and art.

Instructors can use these texts to create courses tailored to their particular needs by approaching the content as an astrophysical smorgasbord. By judiciously selecting topics, we have used BOB to teach a semester-long course in stellar astrophysics. (Of course, much was omitted from the first 18 chapters, but the text is designed to accommodate such surgery.) Interested students have then gone on to take an additional course in cosmology. On the other hand, using the entire text would nicely fill a year-long survey course (and then some) covering all of modern astrophysics. To facilitate the selection of topics, as well as identify important topics within sections, we have added subsection headings to the second editions. Instructors may choose to skim, or even omit, subsections in accordance with their own as well as their students' interests—and thereby design a course to their liking.

Additional resources to accompany this book can be found under the resources tab on the following webpage: www.cambridge.org/astrophysics. It contains downloadable versions of the computer codes in various languages, including Fortran, C++, and, in some cases, Java. There are also links to some of the many important websites in astronomy. In addition, links are provided to public domain images found in the texts, as well as to line art that can be used for instructor presentations. Instructors may also obtain a detailed solutions manual directly from the publisher.

Throughout the process of the extensive revisions for the second editions, our editors have maintained a positive and supportive attitude that has sustained us throughout. Although we must have sorely tried their patience, Adam R. S. Black, Lothlórien Homet, Ashley Taylor Anderson, Deb Greco, Stacie Kent, Shannon Tozier, and Carol Sawyer (at Techsetters) have been truly wonderful to work with.

We have certainly been fortunate in our professional associations throughout the years. We want to express our gratitude and appreciation to Art Cox, John Cox (1926–1984), Carl Hansen, Hugh Van Horn, and Lee Anne Willson, whose profound influence on us has remained and, we hope, shines through the pages ahead.

Our good fortune has been extended to include the many expert reviewers who cast a merciless eye on our chapters and gave us invaluable advice on how to improve them. For their careful reading of the first editions, we owe a great debt to Robert Antonucci, Martin Burkhead, Peter Foukal, David Friend, Carl Hansen, H. Lawrence Helfer, Steven D. Kawaler, William Keel, J. Ward Moody, Tobias Owen, Judith Pipher, Lawrence Pinsky, Joseph Silk, J. Allyn Smith, and Rosemary Wyse. Additionally, the extensive revisions to the second editions have been carefully reviewed by Bryon D. Anderson, Markus J. Aschwanden, Andrew Blain, Donald J. Bord, Jean-Pierre Caillault, Richard Crowe, Manfred A. Cuntz, Daniel Dale, Constantine Deliyannis, Kathy DeGioia Eastwood, J. C.

Evans, Debra Fischer, Kim Griest, Triston Guillot, Fred Hamann, Jason Harlow, Peter Hauschildt, Lynne A. Hillenbrand, Philip Hughes, William H. Ingham, David Jewitt, Steven D. Kawaler, John Kielkopf, Jeremy King, John Kolena, Matthew Lister, Donald G. Luttermoser, Geoff Marcy, Norman Markworth, Pedro Marronetti, C. R. O'Dell, Frederik Paerels, Eric S. Perlman, Bradley M. Peterson, Slawomir Piatek, Lawrence Pinsky, Martin Pohl, Eric Preston, Irving K. Robbins, Andrew Robinson, Gary D. Schmidt, Steven Stahler, Richard D. Sydora, Paula Szkody, Henry Throop, Michael T. Vaughn, Dan Watson, Joel Weisberg, Gregory G. Wood, Matt A. Wood, Kausar Yasmin, Andrew Youdin, Esther Zirbel, E. J. Zita, and others. Over the past decade, we have received valuable input from users of the first-edition texts that has shaped many of the revisions and corrections to the second editions. Several generations of students have provided us with a different and extremely valuable perspective as well. Unfortunately, no matter how fine the sieve, some mistakes are sure to slip through, and some arguments and derivations may be less than perfectly clear. The responsibility for the remaining errors is entirely ours, and we invite you to submit comments and corrections to us at our e-mail address: `modastro@weber.edu`.

Unfortunately, the burden of writing has not been confined to the authors but was unavoidably shared by family and friends. We wish to thank our parents, Wayne and Marjorie Carroll, and Dean and Dorothy Ostlie, for raising us to be intellectual explorers of this fascinating universe. Finally, it is to those people who make *our* universe so wondrous that we dedicate this book: our wives, Lynn Carroll and Candy Ostlie, and Dale's terrific children, Michael and Megan. Without their love, patience, encouragement, and constant support, this project would never have been completed.

And now it is time to get up into Utah's beautiful mountains for some skiing, hiking, mountain biking, fishing, and camping and share those down-to-Earth joys with our families!

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