Interstellar and Intergalactic Medium

This concise textbook, the first volume in the Ohio State Astrophysics Series, covers all aspects of the interstellar and intergalactic medium for graduate students and advanced undergraduates. This series aims to impart the essential knowledge on a topic that every astrophysics graduate student should know, without going into encyclopedic depth. This text includes a full discussion of the circumgalactic medium, which bridges the space between the interstellar and intergalactic gas, and the hot intracluster gas that fills clusters of galaxies. Its breadth of coverage is innovative, as most current textbooks treat the interstellar medium in isolation. The authors emphasize an order-of-magnitude understanding of the physical processes that heat and cool the low-density gas in the universe, as well as the processes of ionization, recombination, and molecule formation. Problems at the end of each chapter are supplemented by online projects, data sets, and other resources.

BARBARA RYDEN received her Ph.D. in Astrophysical Sciences from Princeton University. After postdocs at the Harvard-Smithsonian Center for Astrophysics and the Canadian Institute for Theoretical Astrophysics, she joined the astronomy faculty at The Ohio State University, where she is now a full professor. She has more than 25 years of experience in teaching, at levels ranging from introductory undergraduate courses to advanced graduate seminars. She won the Chambliss Astronomical Writing Award for her textbook *Introduction to Cosmology*. She is co-author, with Bradley M. Peterson, of one of the market leading astrophysics texts, *Foundations of Astrophysics*.

RICHARD W. POGGE received his Ph.D. in Astronomy & Astrophysics from the University of California Santa Cruz. Following postdocs at the University of Texas at Austin and The Ohio State University, he joined the astronomy faculty at OSU where he is a full professor and vice-chair for instrumentation. His research includes observational spectrophotometry of the astrophysics of gaseous nebulae from interstellar gas to active galactic nuclei using ground- and space-based observatories from radio to X-ray. He has over 40 years of experience teaching both undergraduate and graduate courses.

Interstellar and Intergalactic Medium

Barbara Ryden

The Ohio State University

Richard W. Pogge

The Ohio State University

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

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

314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, 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/9781108478977
DOI: 10.1017/9781108781596

First published 2021

Printed in the United Kingdom by TJ Books Limited, Padstow Cornwall

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

ISBN 978-1-108-47897-7 Hardback
ISBN 978-1-108-74877-3 Paperback

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

For Jill Knapp and Bruce Draine, as a belated thank you. BR

For Donald Edward Osterbrock (1924–2007), who taught me how to be a scientist. RWP

Contents

Preface

The idea of writing this textbook was triggered in the 2012/2013 academic year, when The Ohio State University switched from a quarter-based calendar to a semester-based calendar. In the revised curriculum, first-year graduate students take a five credit-hour course "Observed Properties of Astronomical Systems." This is followed by six courses, each of two or three credit-hours: "Atomic and Radiative Processes in Astrophysics," "Stellar Structure and Evolution," "Dynamics," "Cosmology," "Numerical and Statistical Methods in Astrophysics," and "The Interstellar Medium and the Intergalactic Medium." The philosophy of the OSU graduate program, however, is best encapsulated in the two credit-hour course "Order of Magnitude Astrophysics," which is offered every year to first- and second-year students. In this course, students work together to solve a wide range of astrophysical problems, using basic physical principles to find back-of-envelope solutions.

The Ohio State Astrophysics Series (OSAS), of which this is the first volume, is a projected series of books based on lecture notes for the six core courses and the first-year "Observed Properties" course. These textbooks will not be exhaustive monographs but will instead adopt the back-of-envelope philosophy of the "Order of Magnitude" course to emphasize the most important physical principles in each subfield of astrophysics. The goal is to make our series a point of entry into the deeper and more detailed classic textbooks in our field. Although each volume in OSAS will stand on its own, care will be taken to unify the notation and vocabulary as much as possible across volumes.

Interstellar and Intergalactic Medium is based on the semester-long class "The Interstellar Medium and the Intergalactic Medium." The textbook uses the cgs (centimeter, gram, second) system of units, as is common in graduate education in astronomy. It also uses the most common astronomical distance units: the solar radius ($R_\odot$), the astronomical unit (au), and the parsec (pc). In addition, masses are given in units of the solar mass ($M_\odot$) and luminosities in units of the solar luminosity ($L_\odot$). On small scales, when we examine individual

photons and other particles, the electron-volt (eV) will be a useful small unit of energy, with 1 eV $= 1.602 \times 10^{-12}$ erg. Other helpful conversion factors, and the values of physical and astronomical constants, are included in tables at the back of the book.

To keep the length of this book under control, we do not provide a review of spectroscopic notation. (This subject is covered in the course "Atomic and Radiative Processes" at Ohio State University.) If spectroscopic symbols such as $^3P_0$ and $^1\Sigma_g^+$ are not part of your symbolic vocabulary, our brief guide to spectroscopic notation can be downloaded from the Cambridge University Press website for this book. The website contains other ancillary materials such as additional end-of-chapter problems and links to Jupyter notebooks for recreating and modifying figures in the textbook.

A preliminary version of this text was made as an electronic book during the 2014 Book Launch program of the Office of Distance Education and eLearning (ODEE) at Ohio State University. Ashley Miller, Michael Shiflet, and the entire ODEE team were a perpetual source of assistance. The volume you are now reading is a thorough revision of the 2014 e-book. The revision was greatly aided by the graduate students of Adam Leroy (Ohio State University) and Evan Skillman (University of Minnesota). These students, when invited to critique the e-book, gave a wide array of useful (and mostly tactful) feedback.

Many of the figures and images in this book are derived from works in the published astronomical literature. We are grateful to the authors and journals who promptly granted permission to use their figures. We are especially grateful to those of our colleagues who dug out their original data for us to replot for this volume. Particular thanks are due to Adwin Boogert (University of Hawaii) for Figure 6.7, Bruce Draine (Princeton University) and Aigen Li (University of Missouri) for Figure 6.8, Joseph Weingartner (George Mason University) for Figure 6.10, Sanskriti Das and Smita Mathur (Ohio State University) for Figures 8.2, 8.3, and 10.6, Fabio Gastaldello (INAF-IASF Milan) for Figure 8.6, Bill Keel (University of Alabama) for Figure 9.1, Xiaohui Fan and Feige Wang (University of Arizona) for Figure 9.2, Stephan Frank (Ohio State University) for Figure 9.7, and Davide Martizzi (Copenhagen) for Figures 10.2, 10.3, and 10.4.