

To Measure the Sky

An Introduction to Observational Astronomy

Second Edition

The second edition of this popular text provides undergraduates with a quantitative yet accessible introduction to the physical principles underlying the collection and analysis of observational data in contemporary optical and infrared astronomy. The text clearly links recent developments in ground- and space-based telescopes, observatory and instrument design, adaptive optics, and detector technologies to the more modest telescopes and detectors students may use themselves. Beginning with reviews of the most relevant physical concepts and an introduction to elementary statistics, students are given the firm theoretical foundation they need. New topics, including an expanded treatment of spectroscopy, Gaia, the Large Synoptic Survey Telescope, and photometry at large redshifts bring the text up to date. Historical development of topics and quotations emphasize that astronomy is both a scientific and a human endeavor, while extensive end-of-chapter exercises facilitate the students' practical learning experience.

Frederick R. Chromey is Professor of Astronomy on the Matthew Vassar, Jr. Chair at Vassar College, and Director of the Vassar College Observatory. He has almost 45 years' experience in observational astronomy research in the optical, radio, and near infrared on stars, gaseous nebulae, and galaxies, and has taught astronomy to undergraduates at Brooklyn College and Vassar.

To Measure the Sky

An Introduction to Observational Astronomy

Second Edition

Frederick R. Chromey

Vassar College, New York



CAMBRIDGE
UNIVERSITY PRESS



Shaftesbury Road, Cambridge CB2 8EA, 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
103 Penang Road, #05–06/07, Visioncrest Commercial, Singapore 238467

Cambridge University Press is part of Cambridge University Press & Assessment, a department of the University of Cambridge.

We share the University's mission to contribute to society through the pursuit of education, learning and research at the highest international levels of excellence.

www.cambridge.org

Information on this title: www.cambridge.org/9781107572560

© Frederick R. Chromey 2016

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press & Assessment.

First published 2016

6th printing 2022

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

Library of Congress Cataloging-in-Publication data

Names: Chromey, Frederick R., 1944-

Title: To measure the sky : an introduction to observational astronomy /

Frederick R. Chromey, Vassar College, New York.

Other titles: Observational astronomy

Description: Second edition. | Cambridge : Cambridge University Press, [2016] |

Includes bibliographical references and index.

Identifiers: LCCN 2016012710 | ISBN 9781107572560 (Hardback : alk. paper)

Subjects: LCSH: Astronomy—Observations—Textbooks. |

Astronomy—Technique—Textbooks. | Astronomy—Textbooks.

Classification: LCC QB145 .C525 2016 | DDC 522—dc23 LC record available at <http://lcn.loc.gov/2016012710>

ISBN 978-1-107-57256-0 Paperback

Cambridge University Press & Assessment has no responsibility for the persistence or accuracy of URLs for external or third-party internet websites referred to in this publication and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

To Molly

Contents

Preface	<i>page xi</i>
1 Light	1
1.1 The story	1
1.2 Models for the behavior of light	3
1.3 Measurements of light rays	9
1.4 Spectra	13
1.5 Magnitudes	22
Summary	28
Exercises	29
2 Uncertainty	32
2.1 Accuracy and precision	32
2.2 Describing populations	38
2.3 Probability distributions	43
2.4 Estimating uncertainty	48
2.5 Propagation of uncertainty	51
2.6 Additional topics	55
Summary	55
Exercises	56
3 Place, time, and motion	59
3.1 Astronomical coordinate systems	59
3.2 The third dimension	77
3.3 Time	82
3.4 Motion	87
Summary	92
Exercises	94
4 Names, catalogs, and databases	97
4.1 Star names	98
4.2 Non-stellar objects outside the Solar System	102

4.3	Objects at non-optical wavelengths	105
4.4	Atlases, finding charts, and sky surveys	105
4.5	Solar System objects	108
4.6	Websites and other computer resources	109
	Summary	110
	Exercises	111
5	Optics for astronomy	113
5.1	Principles of geometrical optics	113
5.2	Lenses, mirrors, and simple optical configurations	124
5.3	Simple telescopes	130
5.4	Image quality: telescopic resolution	133
5.5	Aberrations	135
	Summary	146
	Exercises	147
6	Astronomical telescopes	150
6.1	Telescope mounts and drives	150
6.2	Reflecting telescope optics	153
6.3	Telescopes in space	162
6.4	The current revolution in ground-based observing	169
6.5	Atmospheric blur	174
6.6	Adaptive optics	177
6.7	Extremely large telescopes	187
	Summary	189
	Exercises	190
7	Matter and light	193
7.1	Isolated atoms	193
7.2	Isolated molecules	200
7.3	Solid-state crystals	202
7.4	Photoconductors	214
7.5	The MOS capacitor	216
7.6	The p–n junction	218
7.7	The vacuum photoelectric effect	222
7.8	Superconductivity	224
	Summary	228
	Exercises	229
8	Detectors	232
8.1	Detector characterization	232
8.2	The CCD	239
8.3	CMOS arrays	256

8.4 Infrared arrays	256
8.5 Photo-emissive devices	261
8.6 Thermal detectors	265
Summary	267
Exercises	268
9 Digital images from arrays	271
9.1 Arrays	271
9.2 Digital image manipulation	276
9.3 Preprocessing array data: bias, linearity, dark, flat, and fringe	281
9.4 Combining images	293
9.5 Digital aperture photometry	304
Summary	313
Exercises	314
10 Photometry	316
10.1 Introduction: a short history	317
10.2 The photometric response function	319
10.3 The idea of a photometric system	329
10.4 Common photometric systems	330
10.5 Absorption by the atmosphere	336
10.6 Transformation to a standard system	348
10.7 Absorption outside the atmosphere	349
10.8 Wavelength changes	353
Summary	357
Exercises	358
11 Spectroscopy	362
11.1 Dispersive spectrometry	363
11.2 Dispersing optical elements	365
11.3 Spectrometers without slits	374
11.4 Basic slit and fiber spectrometers	375
11.5 Single-object spectrometer design for astronomy	379
11.6 Multiplexed spectrometers	382
11.7 Spectrometer stability and mounting	388
11.8 Data acquisition and reduction	389
11.9 Interpreting spectra	395
Summary	412
Exercises	414
Appendices	417
References	451
Index	455

Preface

There is an old joke: a lawyer, a priest, and an observational astronomer walk into a bar. The bartender turns out to be a visiting extraterrestrial who presents the trio with a complicated-looking black box. The alien first demonstrates that when a bucketful of garbage is fed into the entrance chute of the box, a small bag of high-quality diamonds and a gallon of pure water appear at its output. Then, assuring the three that the machine is his gift to them, the bartender vanishes.

The lawyer says, “Boys, we’re rich! It’s the goose that lays the golden egg! We need to form a limited partnership so we can keep this thing secret and share the profits.”

The priest says, “No, no, my brothers, we need to take this to the United Nations, so it can benefit all humanity.”

“We can decide all that later,” the observational astronomer says. “Get me a screwdriver. I need to take this thing apart and see how it works.”

The first edition of this text grew out of 16 years of teaching observational astronomy to undergraduates, and this second edition benefited from six years of using that edition in my classes and from hearing from colleagues who had done the same. In both editions, my intent has been partly to satisfy – but mainly to cultivate – my students’ need to look inside black boxes. The text introduces the primary tools for making astronomical observations at visible and infrared wavelengths: telescopes, detectors, cameras, and spectrometers, as well as the methods for securing and understanding the quantitative measurements they make. I hope that after this introduction, none of these tools will remain a completely black box, and that the reader will be ready to use them to pry into other boxes. The second edition has brought the discussion a bit more up to date with current technology and practices, and has added a few recent examples of discoveries that relied on careful application of fundamental practices.

The book, then, aims at an audience similar to my students: nominally second- or third-year science majors, but with a sizable minority containing advanced first-year students, non-science students, and adult amateur astronomers. About three-quarters of those in my classes are *not* bound for graduate school in astronomy or physics, and the text has that set of backgrounds in mind.

I assume my students have little or no preparation in astronomy, but do presume that each has had one year of college-level physics and an introduction to integral and differential calculus. A course in modern physics, although very helpful, is not essential. I make the same assumptions about readers of this book. Since readers' mastery of physics varies, I include reviews of the most relevant physical concepts: optics, atomic structure, and solid-state physics. I also include a brief introduction to elementary statistics. I have written qualitative chapter summaries, but the problems posed at the end of each chapter are all quantitative exercises meant to strengthen and further develop student understanding.

My approach is to be rather thorough on fundamental topics in astronomy, in the belief that individual instructors will supply enrichment in specialized areas as they see fit. The table of contents indicates that my choice of topics is blatantly selective and slanted toward the kind of observations students might make themselves at a campus observatory.

The text lends itself to either a one- or two-semester course. I personally use the book for a two-semester sequence, where, in addition to most of the text and a selection of its end-of-chapter problems, I incorporate a number of at-the-telescope projects both for individuals and for "research teams" of students. I try to vary the large team projects: these have included a photometric time series of a variable object (in different years an eclipsing exoplanetary system, a Cepheid, and a blazar), an H–R diagram, and spectroscopy of the atmosphere of a Jovian planet. I am mindful that astronomers who teach with this text will have their own special interests in particular objects or techniques, and will have their own limitations and capabilities for student access to telescopes and equipment. My very firm belief, though, is that this book will be most effective if the instructor can devise appropriate exercises that require students to put their hands on actual hardware to measure actual photons from the sky.

To use the text for a one-semester course, the instructor will have to judiciously skip many topics. Certainly, if students are well prepared in physics and mathematics, one can dispense with much of Chapters 5 and 6 (geometrical optics and telescopes), Chapter 7 (atomic and solid-state physics), and possibly all detectors (Chapter 8) except the CCD. One would still need to choose between a more thorough treatment of photometry (skipping Chapter 11, on spectrometers) and the inclusion of spectrometry with exclusion of some photometric topics (compressing the early sections of both Chapters 9 and 10).

Compared with other texts, this book has strengths and counterbalancing weaknesses. I have taken some care with the physical and mathematical treatment of basic topics, like detection, uncertainty, telescope design, astronomical seeing, and array processing, but at the cost of a more descriptive or encyclopedic survey of specialized areas of concern to observers (e.g. little treatment of the details of astrometry or of variable star observing). I believe the book is an excellent fit for courses in which students will do their own optical/infrared observing. Because I confine myself to that wavelength region, I can develop

ideas more systematically, beginning with those that arise from fundamental astronomical questions like position, brightness, and spectrum. But that narrowness makes the book less suitable for a more general survey that includes radio or X-ray techniques.

The sheer number of people and institutions contributing to the production of both editions of this book makes an adequate acknowledgment of all those to whom I am indebted impossible. Inadequate thanks are better than none, and I am deeply grateful to all who helped along the way.

A book requires an audience. The audience I had uppermost in mind was filled with those students brave enough to enroll in my Astronomy 240–340 courses at Vassar College. Over the years, more than a hundred of these students have challenged and rewarded me. All made contributions that found their way into this text, but I especially thank those who asked the hardest questions (so sorry this list is incomplete): Liz Blanton, Megan Vogelaar, Claire Webb, Deep Anand, Sherri Stephan, David Hasselbacher, Trent Adams, Leslie Sherman, Kate Eberwein, Olivia Johnson, Iulia Deneva, Laura Ruocco, Ben Knowles, Aaron Warren, Jessica Warren, Gabe Lubell, Scott Fleming, Alex Burke, Colin Wilson, Charles Wisotzkey, Peter Robinson, Tom Ferguson, David Vollbach, Krista Romita, Ximena Fernandez, Max Fagin, Jenna Lemonias, Max Marcus, Rachel Wagner-Kaiser, Tim Taber, Max Fagin, Roni Teich, Zeeve Rogozinski, Alex Shvonski, Nico Mongillo, Lauren Bearden, Angelica Rivera, Megan Lewis, Sean Sellers, Alex Trunnell, Caitlin Rose, and Liz McGrath.

I owe particular thanks to Jay Pasachoff, without whose constant encouragement and timely assistance this book would probably not exist. Likewise, Tom Balonek, who introduced me to CCD astronomy, has shared ideas, data, students, and friendship over many years. I am grateful as well to my astronomical colleagues in the Keck Northeast Astronomical Consortium; all provided crucial discussions on how to thrive as an astronomer at a small college, and many, like Tom and Jay, have read or used portions of the manuscript and the completed first edition in their observational courses. The entire text, and especially the second edition, have benefited from their feedback. I thank every Keckie, but especially Frank Winkler, Eric Jensen, Lee Hawkins, Karen Kwitter, Steve Sousa, Ed Moran, Bill Herbst, Kim McLeod, and Allyson Sheffield.

The anonymous reviewers of my proposal for the second edition made many very helpful suggestions, as did Colette Salyk and Gautham Narayan. I appreciate all the readers of the first edition who have alerted me to errors, and the many excellent conversations with Zosia Krusberg about how to teach science.

Debra Elmegreen, my colleague at Vassar, collaborated with me on multiple research projects and on the notable enterprise of building a campus observatory. Much of our joint experience found its way into this volume. Vassar College, financially and communally, has been a superb environment for both my teaching and my practice of astronomy, and deserves my gratitude. My editors at Cambridge University Press have been uniformly helpful and skilled.

My family and friends have had to bear some of the burden of this writing. Clara Bargellini and Gabriel Camera opened their home to me and my laptop during extended visits, as did my sisters, Nancy and Tina Chromey. Ann Congelton supplied useful quotations and spirited discussions. I thank my children, Kate and Anthony, who gently remind me that what is best in life is not in a book.

Finally, I thank my wife, Molly Shanley, for just about everything.