To Measure the Sky

An Introduction to Observational Astronomy

With a lively yet rigorous and quantitative approach, Frederick R. Chromey introduces the fundamental topics in optical observational astronomy for undergraduates.

Focussing on the basic principles of light detection, telescope optics, coordinate systems and data analysis, the text introduces students to modern observing techniques and measurements. It approaches cutting-edge technologies such as advanced CCD detectors, integral field spectrometers, and adaptive optics through the physical principles on which they are based, helping students to understand the power of modern space and ground-based telescopes, and the motivations for and limitations of future development. Discussion of statistics and measurement uncertainty enables students to confront the important questions of data quality.

It explains the theoretical foundations for observational practices and reviews essential physics to support students' mastery of the subject. Subject understanding is strengthened through over 120 exercises and problems. Chromey's purposeful structure and clear approach make this an essential resource for all student of observational astronomy.

Frederick R. Chromey is Professor of Astronomy on the Matthew Vassar Junior Chair at Vassar College, and Director of the Vassar College Observatory. He has almost 40 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 for 35 years at Brooklyn College and Vassar.

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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 bucket ful 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."

This text grew out of 16 years of teaching observational astronomy to undergraduates, where 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 introductory text, 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 book, then, aims at an audience similar to my students: nominally second- or third-year science majors, but with a sizeable 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. I regard as fundamental:

- the interaction between light and matter at the atomic level, both in the case of the formation of the spectrum of an object and in the case of the detection of light by an instrument
- the role of uncertainty in astronomical measurement
- the measurement of position and change of position
- the reference to and bibliography of astronomical objects, particularly with modern Internet-based systems like *simbad* and *ADS*
- the principles of modern telescope design, including space telescopes, extremely large telescopes and adaptive optics systems
- principles of operation of the charge-coupled device (CCD) and other array detectors; photometric and spectroscopic measurements with these arrays
- treatment of digital array data: preprocessing, calibration, background removal, co-addition and signal-to-noise estimation
- the design of modern spectrometers.

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 the entire text and 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 skip some topics. Certainly, if students are well prepared in physics and mathematics, one can dispense with some or all of Chapter 2 (statistics), Chapter 5 (geometrical optics), and 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), or the inclusion of spectrometry and 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, optical design, astronomical seeing, and space telescopes, 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 the optical/infrared, I can develop ideas more systematically, beginning with those that arise from fundamental astronomical questions like position, brightness, and spectrum. But that confinement to a narrow range of the electromagnetic spectrum 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 this book makes an adequate acknowledgment of all those to whom I am indebted impossible. Inadequate thanks are better than none at all, 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 especially those who asked the hardest questions: Megan Vogelaar Connelly, Liz McGrath, Liz Blanton, 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, Jenna Lemonias, Max Marcus, Rachel Wagner-Kaiser, Tim Taber, Max Fagin, and Claire Webb.

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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, and 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.