Foundations of Astronomy Michael A. Seeds

1990 Edition



# FOUNDATIONS OF ASTRONOMY

1990 EDITION

### MICHAEL A. SEEDS

Joseph R. Grundy Observatory Franklin and Marshall College

**Wadsworth Publishing Company** 

Belmont, California A Division of Wadsworth, Inc. Astronomy Editor: Anne Scanlan-Rohrer Developmental Editor: Mary Arbogast Editorial Assistant: Leslie Width Print Buyer: Martha Branch Art Editor: Marta Kongsle Designer: Julia Scannell Copy Editor: Betty Duncan-Todd Technical Illustrators: Susan Breitbard, Cyndie Clark-Hugel, Innographics, Salinda Tyson Unit Opening Photos: Atlas des Nordlichen gestirnten Himmels für den Anfang des Jahres 1855, p. 10 Chapter Opening Illustrations: Steve Campbell Compositor: Graphic Typesetting Service, Los Angeles Cover Photo: Images of Neptune. Neptune, Neptune's rings, and Neptune's moon Triton as recorded by the Voyager II spacecraft in August 1989. (Courtesy NASA/JPL)

© 1990, 1988, 1986, 1984 by Wadsworth, Inc. All rights reserved. No part of this book may be reproduced, stored in a retrieval system, or transcribed, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior written permission of the publisher, Wadsworth Publishing Company, Belmont, California 94002, a division of Wadsworth, Inc.

Printed in the United States of America

1 2 3 4 5 6 7 8 9 10 --- 94 93 92 91 90

#### Library of Congress Cataloging-in-Publication Data

```
Seeds, Michael A.
Foundations of astronomy / Michael A. Seeds—1990 ed.
p. cm.
Includes bibliographical references.
ISBN 0-534-12768-1
1. Astronomy. I. Title.
QB43.2.S43 1990
520—dc20
89-27118
CIP
```

## To Emery and Helen Seeds

### **PREFACE**

Imagine astronomy without new discoveries, new theories, new instruments, or new images of distant objects. Imagine an astronomy course that never changed year after year. Astronomy is exciting because it has the potential to astonish us with new insights into the secrets of the universe, but we pay a price for that excitement—we must struggle to keep up with a swiftly changing field.

This new edition of *Foundations of Astronomy* includes the newest discoveries and theories as well as the more gradual changes in general opinion among astronomers concerning such things as black holes, active galaxies, and planetary origins. Yet the book is unchanged in its overall approach. It attempts to present astronomy as a unified system of understanding that relates the student's personal existence to the basic processes in the universe.

#### MINIMUM TANGLE

The body of astronomical knowledge resembles a marionette with tangled strings. Each fact, observation, or principle is connected by inferences, assumptions, and theories to other facts, observations, and principles. The teacher's task is to untangle this marionette and make clear the logic of the connections. Just as a marionette has inherent in its design an untangled state, the body of astronomical knowledge has a state that makes the logic of the inferences, assumptions, and theories clearest. In this book, I have attempted to present astronomy in that state of minimum tangle.

By considering stars, galaxies, cosmology, and the solar system in that order, we simplify many of the evidential arguments and intuitive concepts so important to understanding astronomy. For example, by discussing star formation before the solar system, students recognize the solar nebula for what it is, a natural by-product of star formation. More important, by studying stars, galaxies, and cosmology first, students return to the solar system with a cosmic perspective on nature that places them and

their planet into the universe, rather than constructing a universe around them.

Facts can be meaningful only when they are synthesized into a consistent description of nature. Thus, this book views the universe as a small set of natural processes that are responsible for a wide variety of phenomena and that explain a diverse assortment of objects. For example, galaxies, star clusters, individual stars, and planets are all expressions of the same process—gravitational contraction. Only the scale is different. This emphasizing of processes presents astronomy not as a collection of unrelated facts but as a unified body of knowledge.

In addition, this text presents astronomy as a case study in science. It distinguishes between observation and theory, between evidence and conclusion. We want our students to understand how science creates, tests, improves, or discards models of natural phenomena and thus more closely approximates a complete understanding of natural processes.

#### CHANGES IN THE NEW EDITION

Besides including new discoveries, we have carefully refined the presentation of each chapter, in response to comments from a great many instructors and students:

- A new Chapter 1, The Scale of the Cosmos, introduces students to the basic celestial objects and their relative scales. Through its strong graphical content, the chapter also presents the metric system, the astronomical unit, and the light-year.
- Material in the early chapters has been consolidated to better unify the discussions of the celestial sphere, seasons, and lunar phenomena.
   Coordinates and timekeeping have been retained in Appendix A. Optical telescopes, radio and space



- telescopes are now discussed in a single chapter, to emphasize the parallels in their design.
- The material on relativity (once a separate chapter) has been merged into various chapters where it better supports the discussion of astronomical phenomena.
- At the suggestion of many instructors, a new chapter has been added to discuss neutron stars and black holes in greater detail.
- The chapter on peculiar galaxies has been extensively revised and updated to include new observations and the growing synthesis of those observations into a unified understanding of active galactic nuclei.
- The unit on the solar system now emphasizes the solar nebula theory as a unifying theme. Thus the discussion of each solar system object or phenomenon relates the descriptive facts to the solar nebula theory.
- While the solar system chapters follow a
  comparative plan, analyzing basic planetary
  processes by comparing planets with each other,
  the organization has been changed so that each
  planet is presented separately. Data Files—
  containing numerical, photographic, and graphical
  information describing the sun, moon, planets, and
  Comet Halley—have also been added. This
  arrangement presents the unique features of each
  body while still allowing a comparative analysis.
- Observational Activities in Chapters 2, 3, 10, 12, 22, 24, and Appendix A encourage students to make simple observations and guide them in analyzing the implications of what they see. The related Box 8-1 on observing the sun and the supplement, "Observing the Sky," have been retained, with updated tables.
- Students and instructors have responded with enthusiasm to the use of two novel types of illustrations: Film-strip figures, which illustrate temporal processes, and photographs paired with "key" drawings that act as guides to the content of the photographs. (These paired figures have proven especially useful in elucidating complex figures, and they avoid obscuring images with obtrusive labels.)
- At the urging of a number of reviewers, this edition has more end-of-chapter problems spanning a wider range of difficulty.

#### CONTINUING FEATURES

Many useful features have been retained and updated. "Perspectives," which appear at the end of several chapters, introduce new and interesting ideas that allow students to review and apply the principles covered in the chapter. Some Perspectives discuss the development of a theory, the synthesis of hypotheses from data, the testing of theories by observation, and the meaning of statistical evidence.

Study aids for each chapter include a chapter summary, a list of new terms, questions, problems, and recommended readings. The first time the new terms appear in the text they are **bold face**. These same terms are defined in the glossary. The questions are nonquantitative and could lead to essay answers or be used to stimulate class discussion. The problems are quantitative or involve mathematical reasoning. (Answers to even numbered problems appear at the end of the book, and to odd-numbered problems in the *Instructor's Manual*.) The recommended reading, which is intended for the student, ranges from *National Geographic* to *Science*. Instructors may wish to guide students in selecting appropriate reading material.

#### **ACKNOWLEDGMENTS**

My thanks to the many students and teachers who have responded so enthusiastically to *Foundations of Astronomy*. Their comments and suggestions have been very helpful in completing this new edition. I would especially like to thank the numerous reviewers whose careful analysis and thoughtful suggestions have been invaluable in refining *Foundations of Astronomy* as a teaching tool.

The people listed in the illustration credits were very kind in providing photographs and diagrams. Special recognition goes to the following, who were always ready to help locate unusual images from their institutions: Patricia Bridges, US Geological Survey; Jeff Butler, Lancaster County Planning Commission; Linda Carroll, U.S. Geological Survey; Helen S. Horstman, Lowell Observatory; David Malin, Anglo-Australian Observatory; Patricia A. Ross, National Space Science Data Center; Janet Sandland, Royal Observatory Edinburgh; Patricia Shand, Lick Observatory; Jeff L. Stoner, National Optical Astronomy Observatory; Margaret B. Weems, National Radio Astronomy Observatory; Donald E. Wilbur, Pennsylvania Department of Transportation; Denise R. Whitehead, National Optical Astronomy Observatory.



My appreciation also goes to the following institutions for their assistance in providing figures: The Anglo-Australian Observatory, AstroMedia Corporation, *The Astrophysical Journal*, Ames Research Center, Bell Laboratories, Brookhaven National Laboratories, Celestron International, U.S. Geological Survey, High Altitude Observatory, Jet Propulsion Laboratories, Johnson Space Center, Lick Observatory, Lowell Observatory, Lunar and Planetary Laboratory, Martin Marietta Aero-Space Corporation, Mount Wilson and Las Campanas Observatories, National Aeronautics and Space Administration, National Optical Astronomy Observatories, National Radio Astronomy Observatory, Palomar Observatory, Pennsylvania Department of Transportation, Royal Observatory, Edinburgh, and Yerkes Observatory. Many Voyager, Pioneer,

and Mariner photographs were provided by the National Space Science Data Center.

Textbook publishing is a team sport, and the Wadsworth team deserves a trophy. Special thanks go to the editorial and production staff including Jack Carey, Gary Mcdonald, Julia Scannell, James Chadwick, Marty Kongsle, and Karen Hunt. I would especially like to thank Mary Arbogast for her detailed analysis and thoughtful guidance in the creation of this new edition.

Finally, I would like to thank my wife, Janet, and my daughter, Kathryn, for their patience and understanding. Books are made of time, and there is never enough.

Michael A. Seeds Lancaster, Pennsylvania

### A NOTE FROM THE PUBLISHER

The excitement of astronomy lies in new understanding. We see the nitrogen volcanos on Triton and suddenly understand better how planets work in the rigid cold of the outer solar system. To communicate that excitement to students, we must show them how astronomy progresses.

Since 1987 when the previous edition of *Foundations of Astronomy* was written, astronomers have made impressive advances. One team seems to have found an astonishing fast pulsar in the remains of Supernova 1987A, Voyager 2 revealed complex circulation in Neptune's atmosphere, complete rings with imbedded arcs, and a strange, icy geology on Triton. Quasars have been found with red shifts greater than 4, and striking infrared images reveal stars in the act of forming. These and other discoveries are changing astronomy.

In this 1990 edition of *Foundations of Astronomy*, the author has included updates on Neptune (Chapter 23), new telescopes (Chapter 6), Supernova 1987A (Chapter 13), gravity wave detectors (Chapter 14), quasars (Chapter 17), extra solar planets (Chapter 19), SETI

(Chapter 25), and more. The author has added the most recent photographs and diagrams, and has included the latest information about space telescopes, probes to Venus, Jupiter, and Mars, the greenhouse effect, and so on. Following the suggestions of professors who have been using the book, he has also improved the clarity of many discussions. Also, thanks go to the Wadsworth editorial and production team for this edition—Ann Scanlan-Rohrer, Martha Branch, and Mary Douglas.

We view this revision as a necessary update, rather than as a major change (which could require substantial reorganization of an instructor's outline). Therefore, we have been careful to keep the original sequence, page numbering, chapter length, and book length intact, and we have integrated the new material smoothly into the book's original structure. We believe these changes will assist instructors in teaching a current, accurate, and effective course in astronomy. And we hope that students will continue to be fascinated and excited by learning about the universe with the help of *Foundations of Astronomy*.

### TO THE READER

You will approach retirement around the year 2035, and your children about 2060. Your grandchildren will not be retiring until almost 2100. You and your family will live through a century of exploration unlike any in the history of this planet. You will see explorers return to the moon, and your children could be the first colonists in lunar cities. Your grandchildren may reach Mars, mine the asteroid belt, explore the icy satellites of Jupiter and Saturn, or leave the solar system bound for the stars. A century ago the airplane had not been invented. Whatever humanity is like a century in the future, we can guess that it will be deeply involved in the exploration of the solar system. Astronomy, the study of the universe beyond the clouds, helps us understand what we will find when we leave earth.

Living in the next century might be enough justification for taking an astronomy course, but there are other reasons. The coming years will see tremendous advances in science and technology, advances that will confuse anyone not familiar with how science progresses from data to hypothesis to theory to natural law. Should your state permit nuclear waste disposal sites? Should you support construction of orbiting solar power stations? Should you give your children massive doses of vitamin C to combat colds? To resolve such technical issues, you need to apply some of the methods of science. Thus, as you study astronomy in the pages that follow, look at it as an example of scientific reasoning. Distinguish between data and theory, and notice how hypotheses are tested over and over.

Yet another reason for taking an astronomy course is to satisfy your natural curiosity. Having heard about black holes, the expanding universe, or the rings of Saturn, you may want to know more about them. Satisfying your own curiosity is the most noble reason for studying anything.

Curiosity might lead you to consider astronomy as a career, but you should know that the field is very small and jobs are hard to find. Instead, you might consider astronomy as a hobby—an activity for personal satisfaction and enrichment. The magazines listed here will keep you up to date with the rapid advances in the field and give you some ideas for further projects, such as telescope building and astronomical photography:

Astronomy, 411 East Mason St., P.O. Box 92788, Milwaukee, WI 53202 The Griffith Observer, 2800 East Observatory Road, Los Angeles, CA 90027 Mercury, Astronomical Society of the Pacific, 1290 24th Ave., San Francisco, CA 94122 The Planetary Report, The Planetary Society, 65 N. Catalina Ave., Pasadena, CA 91106 Sky and Telescope, Sky Publishing Corporation, 49 Bay State Rd., Cambridge, MA 02238

All these reasons for taking astronomy are reasonable, but the most important reason is astronomy's cultural value. The one reason you should study astronomy, the reason your school goes to the expense of teaching the course for you, is that astronomy tells you about your place in nature. It shows you our tiny planet spinning in space amid a vast cosmos of stars and galaxies. It takes you from the first moment of creation to the end of the universe. You will see our planet form, life develop, and our sun die. This knowledge has no monetary value, but it is priceless if you are to appreciate your existence as a human being.

Astronomy will change you. It will not just expand your horizons, it will do away with them. You will see humanity as part of a complex and beautiful universe. If by the end of this course you do not think of yourself and society differently, if you don't feel excited, challenged, and a bit frightened, then you haven't been paying attention.

## **BRIEF CONTENTS**

1	The Scale of the Cosmos 2
UNIT ONE	THE SKY
2	The Earth and Sky 20
3	Lunar Phases, Tides, and Eclipses 42
4	The Origin of Modern Astronomy 62
5	Newton, Einstein, and Gravity 86
6	Light and Telescopes 108
UNIT TWO	THE STARS
7	Starlight and Atoms 134
8	The Sun—Our Star 155
9	Measuring Stars 182
10	Binary Stars 202
11	The Formation of Stars 220
12	Stellar Evolution 246
13	The Deaths of Stars 264
14	Neutron Stars and Black Holes 281
UNIT THREE	THE UNIVERSE
15	The Milky Way 304
16	Galaxies 330
17	Peculiar Galaxies 352
18	Cosmology 374
UNIT FOUR	THE SOLAR SYSTEM
19	The Origin of the Solar System 398
20	The Earth and Moon 419
21	Mercury, Venus, and Mars 447
22	Jupiter and Saturn 478
23	Uranus, Neptune, and Pluto 511
24	Meteorites, Asteroids, and Comets 537
UNIT FIVE	LIFE
25	Life on Other Worlds 568
26	Afterword 599

### **CONTENTS**

	CHAPTER	Summary—New Terms—Questions—Problems—Recommended Reading—Film	16
	UNIT ONE	THE SKY	10
• •			
	CHAPTER 2	THE EARTH AND SKY 20	
	2.1 2.2 2.3 2.4	The Stars 21 The Celestial Sphere 25 The Motion of the Sun 30 The Motion of the Planets 33 PERSPECTIVE: Climate and Ice Age 36 Summary—New Terms—Questions—Problems—ACTIVITY: The Cycle of Seasons—Recommended Reading 39	
	CHAPTER 3	LUNAR PHASES, TIDES, AND ECLIPSES 42	
	3.1 3.2 3.3 3.4 3.5	The Phases of the Moon 43 The Tides 45 Lunar Eclipses 47 Solar Eclipses 50 Predicting Eclipses 56 Summary—New Terms—Questions—Problems—ACTIVITY: Do-It-Yourself Eclipse Prediction—Recommended Reading 59	
	CHAPTER 4	THE ORIGIN OF MODERN ASTRONOMY 62	
	4.1 4.2 4.3 4.4	The Roots of Astronomy 63 The Copernican Revolution 71 Planetary Motion 76 Modern Astronomy 82 Summary—New Terms—Questions—Problems—Recommended Reading 83	
	CHAPTER 5	NEWTON, EINSTEIN, AND GRAVITY 86	
	5.1 5.2 5.3	Galileo and Newton 87 Orbital Motion 93 Einstein and Relativity 99 Summary—New Terms—Questions—Problems—Recommended Reading 105	

CHAPTER 6	LIGHT AND TELESCOPES 108
6.1 6.2 6.3 6.4 6.5	Radiation: Information from Space 109 Astronomical Telescopes 111 Special Instruments 118 Radio Telescopes 121 Space Astronomy 124 Perspective: The Hubble Space Telescope 128 Summary—New Terms—Questions—Problems—Recommended Reading 128
UNIT TWO	THE STARS
CHAPTER 7	STARLIGHT AND ATOMS 134
7.1	Starlight 135
7.2 7.3 7.4	Atoms 136 The Interaction of Light and Matter 140 Stellar Spectra 145 Summary—New Terms—Questions—Problems—Recommended Reading 152
CHAPTER 8	THE SUN—OUR STAR 155
8.1	The Structure of the Sun and Other Stars 156 Data File 1 The Sun 158
8.2 8.3	The Solar Atmosphere 164 Solar Activity 168 Summary—New Terms—Questions—Problems—Recommended Reading 179
CHAPTER 9	MEASURING STARS 182
9.1	Measuring the Distances to Stars 183
9.2 9.3	Instrinsic Brightness 188 The Diameters of Stars 191
	Perspective: A Neighborhood Survey 198 Summary—New Terms—Questions—Problems—Recommended Reading 196
CHAPTER 10	BINARY STARS 202
10.1 10.2 10.3 10.4	Visual Binaries 203 Spectroscopic Binaries 208 Eclipsing Binaries 212 Stellar Mass and Density 215 Summary—New Terms—Questions—Problems—Activity: Observing Algol—Recommended Reading 217
CHAPTER 11	THE FORMATION OF STARS 220
11.1 11.2	The Interstellar Medium 221 The Birth of Stars 226

11.3 11.4	Nuclear Energy Sources 231  Main-Sequence Stars 234  Perspective: The Orion Nebula 240  Summary—New Terms—Questions—Problems—Recommended Reading 242
CHAPTER 12	STELLAR EVOLUTION 246
12.1 12.2 12.3	Post Main-Sequence Evolution 247 Variable Stars 252 Star Clusters 256 Summary—New Terms—Questions—Problems—ACTIVITY: Naked-Eye Variable Stars—Recommended Reading 261
CHAPTER 13	THE DEATHS OF STARS 264
13.1 13.2 13.3	Lower Main-Sequence Stars 264 The Upper Main Sequence 269 The Evolution of Binary Stars 274 Summary—New Terms—Questions—Problems—Recommended Reading 278
CHAPTER 14	NEUTRON STARS AND BLACK HOLES 281
14.1 14.2	Neutron Stars 281  Black Holes 291  Perspective: SS 433—The Prototype Energy Machine 297  Summary—New Terms—Questions—Problems—Recommended Reading—Science Fiction 300
UNIT THREE	THE UNIVERSE
	THE MILKY WAY 304
15.1 15.2 15.3 15.4	Properties of the Milky Way Galaxy 305 The Origin of the Milky Way 314 Spiral Arms 318 The Nucleus 323 Summary—New Terms—Questions—Problems—Recommended Reading 327
CHAPTER 16	GALAXIES 330
16.1 16.2 16.3	Measuring the Properties of Galaxies 331  The Morphology of Galaxies 337  The Lives of the Galaxies 342  Summary—New Terms—Ouestions—Problems—Recommended Reading 349

CHAPTER 17	PECULIAR GALAXIES 352
17.1 17.2	Active Galaxies 353 Quasars 362 Summary—New Terms—Questions—Problems—Recommended Reading 371
CHAPTER 18	COSMOLOGY 374
18.1 18.2 18.3	The Structure of the Universe 375 The Big Bang 380 Refining the Big Bang: Theory and Observation 386 Summary—New Terms—Questions—Problems—Recommended Reading 393
UNIT FOUR	THE SOLAR SYSTEM
CHAPTER 19	THE ORIGIN OF THE SOLAR SYSTEM 398
19.1	The Great Chain of Origins 399 A Survey of the Solar System 401
19.2 19.3	The Story of Planet Building 410
	Summary—New Terms—Questions—Problems—Recommended Reading 416
CHAPTER 20	THE EARTH AND MOON 419
20.1	Planet Earth 420
20.2	Data File 2 Earth 424 The Moon 429
20.2	Data File 3 The Moon 432
	Summary—New Terms—Questions—Problems—Recommended Reading 444
CHAPTER 21	MERCURY, VENUS, AND MARS 447
21.1	Mercury 448 Data File 4 Mercury 452
21.2	Venus 455 Data File 5 Venus 456
21.3	Mars 464 Data File 6 Mars 466
21.4	The Moons of Mars 474
	Summary—New Terms—Questions—Problems—Recommended Reading 475
CHAPTER 22	JUPITER AND SATURN 478
22.1	Jupiter 478 Data File 7 Jupiter 480
22.2	Jupiter's Family of Moons 488
22.3	Saturn 495
	Data File 8 Saturn 496

503

The Icy Moons of Saturn

22.4

	Summary—New Terms—Questions—Problems—Activity: Observing the Rings of Saturn—Recommended Reading 507
	Salam Recommended
CHAPTER 23	URANUS, NEPTUNE, AND PLUTO 511
23.1	Uranus 512 Data File 9 Uranus 514
23.2	The Moons of Uranus 523
23.3	Neptune 526 Data File 10 Neptune 528
23.4 23.5	The Moons of Neptune 529 Pluto 530
29.9	Data File 11 Pluto 532
	Summary—New Terms—Questions—Problems—Recommended Reading 534
CHAPTER 24	METEORITES, ASTEROIDS, AND COMETS 537
24.1	Meteorites 538
24.2 24.3	Asteroids 544 Comets 549
	Data File 12 Comet Halley 550 Perspective: Collision with a Comet 560
	Summary—New Terms—Questions—Problems—Activity: Observing Meteors—
	Recommended Reading 562
UNIT FIVE	LIFE
CHAPTER 25	LIFE ON OTHER WORLDS 568
25.1 25.2	The Nature of Life 569 The Origin of Life 572
25.3	Communication with Distant Civilizations 581
	Summary—New Terms—Questions—Problems—Recommended Reading 584
CHAPTER 26	AFTERWORD 588
*****	APPENDIXES
APPENDIX A	ASTRONOMICAL COORDINATES AND TIMEKEEPING 590

600

APPENDIX B SYSTEMS OF UNITS

CONTENTS

APPENDIX C ASTRONOMICAL DATA 604

GLOSSARY 615

ANSWERS TO EVEN-NUMBERED PROBLEMS 627

INDEX 629

SUPPLEMENT OBSERVING THE SKY S-1

STAR CHARTS S-7

## **BOXES**

2-1	Magnitudes 24
3-1	THE SMALL-ANGLE FORMULA 52
5-1	Orbital Velocity 95
5-2	ESCAPE VELOCITY 97
6-1	MEASURING THE WAVELENGTH OF LIGHT 111
6-2	THE POWERS OF A TELESCOPE 119
7-1	RADIATION FROM A HEATED OBJECT 137
7-2	Kirchhoff's Laws 143
7-3	THE DOPPLER EFFECT 149
8-1	OBSERVING THE SUN WITH A SMALL TELESCOPE 170
9-1	Parallax and Distance 186
9-2	ABSOLUTE MAGNITUDE 190
9-3	LUMINOSITY, RADIUS, AND TEMPERATURE 192
9-4	SPECTROSCOPIC PARALLAX 197
10-1	THE MASSES OF BINARY STARS 207
11-1	THE MASS-LUMINOSITY RELATION 236
11-2	LIFE EXPECTANCIES OF THE STARS 239
12-1	DEGENERATE MATTER 250
12-2	CEPHEID DISTANCE INDICATORS 255
13-1	Synchrotron Radiation 273
13-2	BEWARE OF LOCAL SUPERNOVAE 275
14-1	Gravitational Radiation 290
15-1	COSMIC RAYS 311
15-2	THE MASS OF THE GALAXY 313
16-1	THE HUBBLE LAW 336
17-1	THE RELATIVISTIC RED SHIFT 365
18-1	THE CURVATURE OF SPACE 379
18-2	THE STEADY STATE THEORY 383
18-3	THE HUBBLE CONSTANT AND THE AGE OF THE UNIVERSE 389
19-1	THE TITIUS-BODE RULE 402
19-2	RADIOACTIVE DATING 409
25-1	GEOLOGIC TIME 577
25-2	COMMUNICATIVE CIVILIZATIONS IN OUR GALAXY 585