



11TH EDITION

DISCOVERING THE UNIVERSE

Neil F. Comins

ESO/F. Kamphues

DISCOVERING THE UNIVERSE

**Eleventh
Edition**

Neil F. Comins *University of Maine*



w. h. freeman

Macmillan Learning

New York

Dedicated to my wife, Suzanne Comins, and to the many students I have had the privilege to teach.

Vice President, STEM: Daryl Fox
Program Director: Brooke Suchomel
Program Manager: Lori Stover
Development Editor: Meg Rosenberg
Associate Editor: Kevin Davidson
Marketing Manager: Leah Christians
Marketing Assistant: Savannah DiMarco
Director of Digital Production: Keri deManigold
Media and Supplements Editor: Victoria Garvey
Director, Content Management Enhancement: Tracey Kuehn
Senior Managing Editor: Lisa Kinne
Senior Content Project Manager: Kerry O'Shaughnessy
Senior Workflow Project Manager: Lisa McDowell
Copyeditor and Indexer: Louise B. Ketz
Senior Photo Editor: Sheena Goldstein
Photo Researchers: Kerri Wilson, Brittani Morgan Grimes
Production Supervisor: Robert Cherry
Director of Design, Content Management: Diana Blume
Design Services Manager: Natasha Wolfe
Interior Design: Lumina Datamatics, Inc.
Cover Design Manager: John Callahan
Cover Design: Kevin Kall
Art Manager: Matt McAdams
Illustrations: Precision Graphics
Composition: Lumina Datamatics, Inc.
Printing and Binding: LSC Communications
Cover Image: ESO/F. Kamphues

Library of Congress Control Number: 2018957930

ISBN-13: 978-1-319-05539-4

ISBN-10: 1-319-05539-7

© 2019, 2014, 2012, 2008 by W. H. Freeman and Company

All rights reserved

Printed in the United States of America

1 2 3 4 5 6 23 22 21 20 19 18

W. H. Freeman and Company
One New York Plaza
Suite 4500
New York, NY 10004-1562
www.macmillanlearning.com

CONTENTS OVERVIEW

| | | | | | | |
|--|---|-------------------------------|--|---|------|-------|
| Preface | xiii | CHAPTER 13 | The Lives of Stars from Birth Through Middle Age | 423 | | |
| About the Author | xix | WHAT IF... | Earth Orbiting a 1.5- M_{\odot} Sun? | 459 | | |
| PART I | | CHAPTER 14 | The Deaths of Stars | 461 | | |
| <hr/> <hr/> | | WHAT IF... | A Supernova Exploded Near Earth? | 492 | | |
| Understanding the Science of Astronomy | | CHAPTER 15 | Black Holes: Matters of Gravity | 495 | | |
| | 1 | PART IV | | | | |
| CHAPTER 1 | Discovering the Night Sky | 5 | <hr/> <hr/> | | | |
| WHAT IF... | Earth's Axis Lay on the Ecliptic? | 42 | Understanding the Universe | | | |
| CHAPTER 2 | Gravitation and the Motion of the Planets | 43 | | 521 | | |
| CHAPTER 3 | Light and Telescopes | 73 | CHAPTER 16 | The Milky Way Galaxy | 525 | |
| WHAT IF... | Humans Had Infrared-Sensitive Eyes? | 117 | CHAPTER 17 | Galaxies | 547 | |
| CHAPTER 4 | Atomic Physics and Spectra | 119 | WHAT IF... | The Solar System were Located Closer to The Center of the Galaxy? | 579 | |
| PART II | | CHAPTER 18 | Quasars and Other Active Galaxies | 583 | | |
| <hr/> <hr/> | | CHAPTER 19 | Cosmology | 601 | | |
| Understanding the Solar System and Exoplanets | | CHAPTER 20 | Astrobiology | 633 | | |
| | 141 | APPENDICES | | | | |
| CHAPTER 5 | Exoplanets and the Formation of Planetary Systems | 145 | A | Powers-of-Ten Notation | A-1 | |
| CHAPTER 6 | Formation of the Solar System | 167 | B | Guidelines for Solving Math Problems and Reading Graphs | A-1 | |
| CHAPTER 7 | Earth and the Moon | 185 | C | Key Formulas | A-4 | |
| WHAT IF... | The Moon Didn't Exist? | 223 | D | Temperature Scales | A-5 | |
| CHAPTER 8 | The Other Terrestrial Planets | 225 | E | Data Tables | A-6 | |
| CHAPTER 9 | The Outer Planets | 269 | F | Periodic Table of the Elements | A-16 | |
| WHAT IF... | We Lived on a Metal-Poor Earth? | 317 | G | Largest Optical Telescopes in the World | A-17 | |
| CHAPTER 10 | Vagabonds of the Solar System | 319 | H | Buying a Telescope | A-19 | |
| CHAPTER 11 | The Sun: Our Extraordinary Ordinary Star | 363 | Glossary | | | G-1 |
| PART III | | Answers to Selected Questions | | | | ANS-1 |
| <hr/> <hr/> | | INDEX | | | | I-1 |
| Understanding the Stars | | 391 | | | | |
| CHAPTER 12 | Characterizing Stars | 395 | | | | |

this page left intentionally blank

| | | | |
|---|------|--|--|
| Preface | xiii | | |
| About the Author | xix | | |
| PART I | | | |
| <hr/> | | | |
| Understanding the Science of Astronomy | 1 | | |
| CHAPTER 1 Discovering the Night Sky | 5 | | |
| SCALES OF THE UNIVERSE | 7 | | |
| 1-1 Astronomical distances are, well, astronomical | 7 | | |
| PATTERNS OF STARS | 8 | | |
| 1-2 Well-known constellations make locating more obscure stars and constellations easy | 9 | | |
| 1-3 The celestial sphere aids in navigating the sky | 11 | | |
| GUIDED DISCOVERY <i>The Stars and Constellations</i> | 13 | | |
| 1-4 An “alt”ernative coordinate system | 14 | | |
| 1-5 Earth orbits the Sun in a plane called the ecliptic | 14 | | |
| EARTHLY CYCLES | 15 | | |
| 1-6 Earth’s rotation creates the day-night cycle and its revolution defines a year | 15 | | |
| AN ASTRONOMER’S TOOLBOX 1-1 <i>Observational Measurements Using Angles</i> | 16 | | |
| 1-7 The seasons result from the tilt of Earth’s rotation axis combined with Earth’s revolution around the Sun | 20 | | |
| 1-8 Clock times based on the Sun’s location created scheduling nightmares | 23 | | |
| 1-9 Calendars based on equal-length years also created scheduling problems | 24 | | |
| 1-10 Precession is a slow, circular motion of Earth’s axis of rotation | 25 | | |
| 1-11 The phases of the Moon originally inspired the concept of the month | 27 | | |
| ECLIPSES | 30 | | |
| 1-12 Eclipses do not occur during every new or full Moon phase | 30 | | |
| 1-13 Three types of lunar eclipse occur | 30 | | |
| 1-14 Three types of solar eclipse also occur | 32 | | |
| 1-15 Frontiers yet to be discovered | 35 | | |
| Summary of Key Ideas | 35 | | |
| WHAT IF... Earth’s Axis Lay on the Ecliptic? | 42 | | |
| CHAPTER 2 Gravitation and the Motion of the Planets | 43 | | |
| SCIENCE: KEY TO COMPREHENDING THE COSMOS | 45 | | |
| 2-1 Science is both a body of knowledge and a process of learning about nature | 45 | | |
| CHANGING OUR EARTH-CENTERED VIEW OF THE UNIVERSE | 47 | | |
| 2-2 The belief in a Sun-centered cosmology formed slowly | 47 | | |
| GUIDED DISCOVERY <i>Earth-Centered Universe</i> | 49 | | |
| 2-3 Copernicus devised the first comprehensive heliocentric cosmology | 50 | | |
| GUIDED DISCOVERY <i>Astronomy’s Foundation Builders</i> | 52 | | |
| 2-4 Tycho Brahe made astronomical observations that disproved ancient ideas about the heavens | 54 | | |
| KEPLER’S AND NEWTON’S LAWS | 55 | | |
| 2-5 Kepler’s laws describe orbital shapes, changing speeds, and the lengths of planetary years | 55 | | |
| 2-6 Galileo’s discoveries strongly supported a heliocentric cosmology | 58 | | |
| AN ASTRONOMER’S TOOLBOX 2-1 <i>Units of Astronomical Distance</i> | 59 | | |
| 2-7 Newton formulated three laws that describe fundamental properties of physical reality | 61 | | |
| AN ASTRONOMER’S TOOLBOX 2-2 <i>Energy and Momentum</i> | 63 | | |
| 2-8 Newton’s description of gravity accounts for Kepler’s laws | 64 | | |
| AN ASTRONOMER’S TOOLBOX 2-3 <i>Gravitational Force</i> | 65 | | |
| 2-9 Orbiting bodies orbit a common center of mass | 65 | | |
| 2-10 Ellipses are not the only paths followed by gravitationally interacting objects | 66 | | |
| 2-11 Frontiers yet to be discovered | 67 | | |
| Summary Of Key Ideas | 69 | | |
| CHAPTER 3 Light and Telescopes | 73 | | |
| ELECTROMAGNETIC RADIATION OBSERVATORIES | 74 | | |
| 3-1 Newton discovered that white is not a fundamental color and proposed that light is composed of particles | 74 | | |
| 3-2 Light travels at a finite but incredibly fast speed | 77 | | |
| 3-3 Einstein showed that light sometimes behaves as particles that carry energy | 78 | | |
| AN ASTRONOMER’S TOOLBOX 3-1 <i>Photon Energies, Wavelengths, and Frequencies</i> | 79 | | |

| | | |
|---|---|-----|
| 3-4 | Visible light is only one type of electromagnetic radiation | 79 |
| OPTICS AND TELESCOPES | | 82 |
| 3-5 | Reflecting telescopes use mirrors to concentrate incoming starlight | 82 |
| 3-6 | Secondary mirrors dim objects but do not create holes in them | 85 |
| 3-7 | Telescopes brighten, resolve, and magnify | 85 |
| 3-8 | Eyepieces, refracting telescopes, and binoculars use lenses to focus incoming light | 88 |
| 3-9 | Shaping telescope mirrors and lenses is an evolving science | 91 |
| 3-10 | Storing and analyzing light from space is key to understanding the cosmos | 92 |
| 3-11 | Earth's atmosphere hinders astronomical research | 94 |
| 3-12 | The Hubble Space Telescope provides stunning details about the universe | 95 |
| 3-13 | Advanced technology is spawning a new generation of superb ground-based telescopes | 96 |
| NONOPTICAL ASTRONOMY | | 98 |
| 3-14 | A radio telescope uses a large concave dish to collect radio waves | 98 |
| 3-15 | Infrared and ultraviolet telescopes also use reflectors to collect electromagnetic radiation | 101 |
| 3-16 | X-ray and gamma-ray telescopes cannot use normal reflectors to gather information | 103 |
| COSMIC RAY OBSERVATORIES | | 106 |
| 3-17 | Cosmic rays are not rays at all | 106 |
| NEUTRINO OBSERVATORIES | | 107 |
| 3-18 | The mystery of the missing neutrinos inspired development of telescopes to detect these elusive particles | 107 |
| GRAVITATIONAL WAVE OBSERVATORIES | | 108 |
| 3-19 | Gravitational radiation observatories provide insights into very violent activities, such as the collisions of stellar remnants | 108 |
| 3-20 | Frontiers yet to be discovered | 112 |
| Summary of Key Ideas | | 112 |
| WHAT IF... Humans Had Infrared-Sensitive Eyes? | | 117 |
| CHAPTER 4 Atomic Physics and Spectra | | 119 |
| BLACKBODY RADIATION | | 120 |
| 4-1 | An object's peak color shifts to shorter wavelengths as it is heated | 120 |
| 4-2 | The intensities of different emitted colors reveal a star's temperature | 122 |
| AN ASTRONOMER'S TOOLBOX 4-1 The Radiation Laws | | 123 |
| GUIDED DISCOVERY The Color of the Sun | | 125 |

| | | |
|--|---|-----|
| IDENTIFYING THE ELEMENTS BY ANALYZING THEIR UNIQUE SPECTRA | | 126 |
| 4-3 | Each chemical element produces its own unique set of spectral lines | 126 |
| 4-4 | The various brightness levels of spectral lines depend on conditions in the spectrum's source | 129 |
| ATOMS AND SPECTRA | | 130 |
| 4-5 | An atom consists of a small, dense nucleus surrounded by electrons | 130 |
| AN ASTRONOMER'S TOOLBOX 4-2 Radioactivity and the Ages of Objects | | 132 |
| 4-6 | Spectra occur because electrons absorb and emit photons with only certain wavelengths | 132 |
| 4-7 | Spectral lines shift due to the relative motion between the source and the observer | 134 |
| AN ASTRONOMER'S TOOLBOX 4-3 The Doppler Shift | | 136 |
| 4-8 | Frontiers yet to be discovered | 137 |
| Summary of Key Ideas | | 137 |

PART II

Understanding the Solar System and Exoplanets

| | | |
|---|---|-----|
| CHAPTER 5 Exoplanets and the Formation of Planetary Systems | | 145 |
| EXOPLANETS—PLANETS OUTSIDE OUR SOLAR SYSTEM | | 146 |
| PLANETS CONTAIN HEAVY ELEMENTS, FORMED IN EARLIER GENERATIONS OF STARS | | 146 |
| 5-1 | Stars transform matter from lighter elements into heavier ones | 146 |
| 5-2 | Gravity, rotation, collisions, and heat shape young star systems | 148 |
| 5-3 | Protoplanetary disks are a common part of the star-forming process | 149 |
| 5-4 | Astronomers have many different ways of detecting planets outside our solar system | 151 |
| METHODS OF DETECTING EXOPLANETS | | 151 |
| 5-5 | Exoplanets orbit a breathtaking variety of stars | 156 |
| 5-6 | Exoplanets with a wide range of sizes, masses, and compositions have been observed | 156 |
| 5-7 | Stars with multiple exoplanets have been observed | 157 |
| 5-8 | Many exoplanets have extraordinary orbits, as compared to those in our solar system | 157 |
| 5-9 | Exoplanets that are not orbiting stars have also been observed | 160 |
| 5-10 | There are billions and billions of exoplanets | 160 |

| | | |
|------------------|---|-----|
| 5-11 | Exoplanets with liquid water are being discovered | 160 |
| 5-12 | Frontiers yet to be explored | 160 |
| | Summary of Key Ideas | 162 |
| | MEET THE DISCOVERERS Dr. John Johnson | 165 |
| CHAPTER 6 | Formation of the Solar System | 167 |
| | THE SOLAR SYSTEM CONTAINS HEAVY ELEMENTS, FORMED FROM AN EARLIER GENERATION OF STARS | 168 |
| 6-1 | The Nice model of the formation of the solar system | 168 |
| | THE FORMATION OF THE PLANETS | 171 |
| 6-2 | The giant planets formed in sequence | 171 |
| 6-3 | The inner planets formed primarily from collisions | 172 |
| 6-4 | The changing orbits of the giant planets caused Uranus and Neptune to spiral out | 172 |
| 6-5 | The solar system had, and still has, a lot of orbiting debris | 173 |
| 6-6 | The asteroid belt is also leftover debris | 174 |
| 6-7 | The infalling debris from the giant planets led to the Late Heavy Bombardment | 175 |
| | CATEGORIES OF THE PRESENT-DAY SOLAR SYSTEM | 176 |
| 6-8 | The categories of solar system objects have evolved | 176 |
| 6-9 | The orbits of the planets are related | 177 |
| 6-10 | The Sun developed while the planets matured | 177 |
| | COMPARATIVE PLANETOLOGY | 178 |
| 6-11 | Comparisons among the eight planets show distinct similarities and significant differences | 178 |
| 6-12 | How does the solar system compare to star systems with known exoplanets? | 181 |
| 6-13 | Frontiers yet to be discovered | 181 |
| | Summary of Key Ideas | 182 |
| CHAPTER 7 | Earth and the Moon | 185 |
| | EARTH: A DYNAMIC, VITAL WORLD | 186 |
| 7-1 | Earth's atmosphere has evolved over billions of years | 186 |
| 7-2 | Plate tectonics produce major changes on Earth's surface | 190 |
| 7-3 | Earth's interior consists of a rocky mantle and an iron-rich core | 194 |
| 7-4 | Earth's magnetic field shields us from the solar wind | 195 |
| | THE MOON AND TIDES | 198 |
| 7-5 | The Moon's surface is covered with craters, plains, and mountains | 198 |
| 7-6 | Visits to the Moon yielded invaluable information about its history | 205 |
| 7-7 | The Moon may have formed from debris cast into space when a huge planetesimal struck the young Earth | 211 |
| 7-8 | Tides have played several important roles in the history of Earth and the Moon | 214 |
| 7-9 | The Moon is moving away from Earth | 215 |
| | GUIDED DISCOVERY Tides | 216 |
| 7-10 | Frontiers yet to be discovered | 218 |
| | SUMMARY OF KEY IDEAS | 218 |
| | WHAT IF... The Moon Didn't Exist? | 223 |
| CHAPTER 8 | The Other Terrestrial Planets | 225 |
| | MERCURY | 227 |
| 8-1 | Photographs from Mariner 10 and MESSENGER spacecraft reveal Mercury's lunarlike surface | 227 |
| 8-2 | Mercury has a higher percentage of iron than Earth | 231 |
| 8-3 | Mercury's rotation and revolution are coupled | 231 |
| 8-4 | Mercury's atmosphere is the thinnest of all terrestrial planets | 233 |
| | VENUS | 234 |
| 8-5 | The surface of Venus is completely hidden beneath a permanent cloud cover | 234 |
| | GUIDED DISCOVERY The Inner Solar System | 235 |
| 8-6 | The greenhouse effect heats Venus's surface | 236 |
| 8-7 | Venus is covered with gently rolling hills, two "continents," and numerous volcanoes | 238 |
| | MARS | 241 |
| 8-8 | Mars's global features include plains, canyons, craters, and volcanoes | 242 |
| 8-9 | Although no canals exist on Mars, it does have some curious natural features | 246 |
| 8-10 | Mars's interior is less molten than the inside of Earth | 246 |
| 8-11 | Martian air is thin and often filled with dust | 249 |
| 8-12 | Surface and underground features indicate that water once flowed and may still flow in small quantities on Mars | 251 |
| 8-13 | Search for microscopic life on Mars continues | 257 |
| 8-14 | Mars's two moons look more like potatoes than spheres | 258 |
| | COMPARATIVE PLANETOLOGY OF THE INNER PLANETS | 259 |
| 8-15 | Comparisons of planetary features provide new insights | 259 |
| 8-16 | Frontiers yet to be discovered | 261 |
| | Summary of Key Ideas | 262 |
| | MEET THE DISCOVERERS Dr. Briony Horgan | 267 |

| | |
|---|-----|
| CHAPTER 9 The Outer Planets | 269 |
| JUPITER | 270 |
| 9-1 Jupiter's outer layer is a dynamic area of storms and turbulent gases | 270 |
| 9-2 Our understanding of Jupiter's interior is in flux | 275 |
| 9-3 Impacts provide probes into Jupiter's atmosphere | 276 |
| JUPITER'S MOONS AND RINGS | 279 |
| 9-4 Io's surface is sculpted by volcanic activity | 279 |
| 9-5 Europa harbors liquid water below its surface | 282 |
| 9-6 Ganymede is larger than Mercury | 284 |
| 9-7 Callisto bears the scars of a huge asteroid impact | 285 |
| 9-8 Other debris orbits Jupiter as smaller moons and ringlets | 286 |
| SATURN | 287 |
| 9-9 Saturn's atmosphere, surface, and interior are similar to those of Jupiter | 287 |
| 9-10 Saturn's spectacular rings are composed of fragments of ice and ice-coated rock | 291 |
| 9-11 Titan has a thick atmosphere, clouds, and lakes filled with liquids | 297 |
| 9-12 Rhea has ice | 299 |
| 9-13 Enceladus has water jets, an atmosphere, and a magnetic field | 300 |
| URANUS | 302 |
| 9-14 Uranus sports a hazy atmosphere and clouds | 302 |
| 9-15 A system of rings and satellites revolves around Uranus | 304 |
| NEPTUNE | 306 |
| 9-16 Neptune was discovered because it had to be there | 307 |
| 9-17 Neptune has rings and captured moons | 308 |
| COMPARATIVE PLANETOLOGY OF THE OUTER PLANETS | 310 |
| 9-18 Frontiers yet to be discovered | 310 |
| Summary Of Key Ideas | 312 |
| WHAT IF... We Lived on a Metal-Poor Earth? | 317 |
| CHAPTER 10 Vagabonds of the Solar System | 319 |
| DWARF PLANETS | 320 |
| 10-1 Pluto and its moon, Charon, are about the same size | 320 |
| 10-2 Ceres is a dwarf planet in the asteroid belt, while Pluto, Eris, Haumea, and Makemake are trans-Neptunian objects as well as dwarf planets | 325 |
| SMALL SOLAR SYSTEM BODIES | 327 |
| ASTEROIDS | 327 |
| 10-3 Most asteroids orbit the Sun between Mars and Jupiter | 327 |

| | |
|--|-----|
| 10-4 Jupiter's gravity creates gaps in the asteroid belt | 329 |
| 10-5 Asteroids also orbit outside the asteroid belt | 333 |
| COMETS | 335 |
| 10-6 Comets come from far out in the solar system | 336 |
| 10-7 Comet tails develop from gases and dust pushed outward by the Sun | 340 |
| 10-8 Comets are fragile yet durable | 343 |
| 10-9 Comets do not last forever | 344 |
| METEORIODS, METEORS, AND METEORITES | 348 |
| 10-10 Small, rocky debris peppers the solar system | 348 |
| 10-11 Meteorites are space debris that land intact | 350 |
| 10-12 The Allende meteorite provides evidence of catastrophic explosions | 354 |
| 10-13 Asteroid impacts with Earth have caused mass extinctions | 354 |
| 10-14 Frontiers yet to be discovered | 356 |
| Summary of Key Ideas | 357 |
| MEET THE DISCOVERERS Dr. Cristina Thomas | 362 |
| CHAPTER 11 The Sun: Our Extraordinary Ordinary Star | 363 |
| THE SUN'S ATMOSPHERE | 365 |
| 11-1 The photosphere is the visible layer of the Sun | 365 |
| 11-2 The chromosphere is characterized by spikes of gas called spicules | 366 |
| 11-3 The outermost layer of the Sun's atmosphere, the corona, is exceptionally hot | 367 |
| 11-4 The solar wind produces the heliosphere that surrounds the solar system | 368 |
| THE ACTIVE SUN | 370 |
| 11-5 Sunspots reveal the solar cycle and the Sun's rotation | 371 |
| 11-6 The Sun's magnetic fields create sunspots | 373 |
| 11-7 Solar magnetic fields also create other atmospheric phenomena | 376 |
| THE SUN'S INTERIOR | 379 |
| 11-8 Thermonuclear reactions in the core of the Sun produce its energy | 379 |
| 11-9 The solar model describes how energy escapes from the Sun's core | 380 |
| 11-10 The Sun has gotten brighter over time | 381 |
| AN ASTRONOMER'S TOOLBOX 11-1 Thermonuclear Fusion | 382 |
| 11-11 Neutrinos from the Sun and other sources are providing new insights into high-energy activity in space | 385 |
| 11-12 Frontiers yet to be discovered | 386 |
| Summary of Key Ideas | 386 |

PART III

Understanding the Stars 391**CHAPTER 12 Characterizing Stars** 395

12-1 Distances to nearby stars are found using stellar parallax 396

AN ASTRONOMER'S TOOLBOX 12-1 **Distances to Nearby Stars** 398

AN ASTRONOMER'S TOOLBOX 12-2 **Details of the Magnitude Scales** 399

MAGNITUDE SCALES 399

12-2 Apparent magnitude measures the brightness of stars as seen from Earth 399

12-3 Absolute magnitudes and luminosities do not depend on distance 401

GUIDED DISCOVERY **Star Names** 402

AN ASTRONOMER'S TOOLBOX 12-3 **The Distance-Magnitude Relationship** 403

THE TEMPERATURES OF STARS 403

12-4 A star's color reveals its surface temperature 404

12-5 A star's spectrum also reveals its surface temperature 404

12-6 Stars are classified by their spectra 406

TYPES OF STARS 407

12-7 The Hertzsprung-Russell diagram identifies distinct groups of stars 408

12-8 Luminosity classes set the stage for understanding stellar evolution 409

12-9 A star's spectral type and luminosity class provide a second distance-measuring technique 410

STELLAR MASSES 411

12-10 Binary stars provide information about stellar masses 411

AN ASTRONOMER'S TOOLBOX 12-4 **Kepler's Third Law and Stellar Masses** 412

12-11 Main-sequence stars have a relationship between mass and luminosity 415

12-12 The orbital motion of binary stars affects the wavelengths of their spectral lines 415

12-13 Frontiers yet to be discovered 417

Summary of Key Ideas 418

CHAPTER 13 The Lives of Stars from Birth Through Middle Age 423**PROTOSTARS AND PRE-MAIN-SEQUENCE STARS** 424

13-1 Gas and dust exist between the stars 424

13-2 Supernovae, collisions of interstellar clouds, and starlight trigger new star formation 428

GUIDED DISCOVERY **Observing the Nebulae** 430

13-3 When a protostar ceases to accumulate mass, it becomes a pre-main-sequence star 430

13-4 The evolutionary track of a pre-main-sequence star depends on its mass 432

GUIDED DISCOVERY **Extrasolar Planets and Brown Dwarfs** 433

13-5 H II regions harbor young star clusters 435

13-6 Plotting a star cluster on an H-R diagram reveals its age 436

MAIN-SEQUENCE AND GIANT STARS 439

13-7 Stars spend most of their lives on the main sequence 439

EVOLUTION OF STARS WITH MASSES BETWEEN 0.08 M_⊙ AND 0.4 M_⊙ 441

13-8 Red dwarfs convert essentially their entire mass into helium 441

EARLY AND MIDDLE EVOLUTION OF STARS WITH MORE THAN 0.4 M_⊙ 442

13-9 When core hydrogen fusion slows down, a main-sequence star with mass greater than 0.4 M_⊙ becomes a giant 442

13-10 Helium fusion begins at the center of a giant 444

13-11 Life in the giant phase has its ups and downs 445

VARIABLE STARS 445

13-12 A Cepheid pulsates because it is alternately expanding and contracting 446

13-13 Cepheids enable astronomers to estimate vast distances 447

13-14 Globular clusters are bound groups of old stars 447

13-15 Mass transfer in close binary systems can produce unusual double stars 451

13-16 Frontiers yet to be discovered 453

Summary of Key Ideas 454

WHAT IF... Earth Orbiting a 1.5-M_⊙ Sun? 459

CHAPTER 14 The Deaths of Stars 461**LOW-MASS (0.4 M_⊙–8 M_⊙) STARS AND PLANETARY NEBULAE** 462

14-1 Low-mass stars become supergiants before expanding into planetary nebulae 463

14-2 The burned-out core of a low-mass star becomes a white dwarf 465

14-3 White dwarfs in close binary systems can create powerful explosions 466

14-4 Accreting white dwarfs in close binary systems can also explode as Type Ia supernovae 468

HIGH-MASS (GREATER THAN 8 M_⊙) STARS AND TYPE II SUPERNOVAE 469

14-5 A series of fusion reactions in high-mass stars leads to luminous supergiants 469

| | | |
|---|---|-----|
| 14-6 | High-mass stars blow apart in Type II supernova explosions | 470 |
| 14-7 | Supernova remnants are observed in many places | 472 |
| 14-8 | Supernova 1987A offered a detailed look at a massive star's death | 474 |
| 14-9 | Cosmic rays are not rays at all | 476 |
| NEUTRON STARS AND PULSARS | | 476 |
| 14-10 | The cores of many Type II supernovae become neutron stars | 476 |
| 14-11 | A rotating magnetic field explains the pulses from a neutron star | 477 |
| 14-12 | Rotating neutron stars create other phenomena besides normal pulsars | 479 |
| 14-13 | Neutron stars have internal structure | 481 |
| 14-14 | Some pulsars are in binary systems | 481 |
| 14-15 | Superluminous supernovae are much brighter than either Type Ia or Type II supernovae | 482 |
| 14-16 | Supernova impostors | 482 |
| 14-17 | Fast radio bursts | 484 |
| 14-18 | Colliding neutron stars provide most of the heavy elements in the universe | 484 |
| 14-19 | Binary neutron stars create pulsating X-ray sources | 485 |
| 14-20 | Neutron stars in binary systems can also emit powerful isolated bursts of X-rays | 486 |
| 14-21 | Frontiers yet to be discovered | 488 |
| Summary of Key Ideas | | 488 |
| WHAT IF... A Supernova Exploded Near Earth? | | 492 |
| MEET THE DISCOVERERS Dr. Anna Frebel | | 493 |
| CHAPTER 15 Black Holes: Matters of Gravity | | 495 |
| THE RELATIVITY THEORIES | | 496 |
| 15-1 | Special relativity changes our conception of space and time | 496 |
| 15-2 | General relativity explains how matter warps spacetime, thereby creating gravitational attraction | 498 |
| 15-3 | Spacetime affects the behavior of light | 499 |
| 15-4 | General relativity predicts the fate of massive stellar cores—black holes | 500 |
| AN ASTRONOMER'S TOOLBOX 15-1 The Sizes of Black Holes | | 501 |
| INSIDE A BLACK HOLE | | 501 |
| 15-5 | Matter in a black hole becomes much simpler than elsewhere in the universe | 501 |
| 15-6 | Falling into a black hole is an infinite voyage | 502 |
| GRAVITATIONAL RADIATION | | 504 |
| FURTHER EVIDENCE FOR BLACK HOLES | | 506 |
| 15-7 | Several binary star systems contain black holes | 506 |
| 15-8 | Other black holes range in mass up to billions of solar masses | 506 |
| GUIDED DISCOVERY Identifying Stellar-Remnant Black Holes | | 507 |

| | | |
|---|---|-----|
| 15-9 | Black holes and neutron stars in binary systems often create jets of gas | 510 |
| 15-10 | Black holes evaporate | 510 |
| GAMMA-RAY BURSTS | | 512 |
| 15-11 | Gamma-ray bursts are the most powerful explosions in the known universe | 512 |
| 15-12 | Frontiers yet to be discovered | 514 |
| Summary of Key Ideas | | 514 |
| MEET THE DISCOVERER Dr. Scott A. Hughes | | 518 |
| PART IV | | |
| <hr/> | | |
| Understanding the Universe | | 521 |
| CHAPTER 16 The Milky Way Galaxy | | 525 |
| DEFINING THE MILKY WAY | | 527 |
| 16-1 | Studies of Cepheid variable stars revealed that the Milky Way is only one of many galaxies | 527 |
| AN ASTRONOMER'S TOOLBOX 16-1 Cepheids and Type Ia Supernovae as Indicators of Distance | | 530 |
| THE STRUCTURE OF OUR GALAXY AND OUR PLACE IN IT | | 529 |
| 16-2 | Cepheid variables help us locate our Galaxy's center | 530 |
| 16-3 | Nonvisible observations help map the galactic disk | 531 |
| 16-4 | The Milky Way has a global magnetic field | 534 |
| 16-5 | The galactic nucleus is an active, crowded place | 534 |
| 16-6 | Our Galaxy's disk is surrounded by a two-shell spherical halo of stars and other matter | 539 |
| 16-7 | The Galaxy is rotating | 540 |
| MYSTERIES AT THE GALACTIC FRINGES | | 542 |
| 16-8 | Most of the matter in the Galaxy has not yet been identified | 542 |
| 16-9 | Frontiers yet to be discovered | 542 |
| Summary of Key Ideas | | 543 |
| CHAPTER 17 Galaxies | | 547 |
| TYPES OF GALAXIES | | 548 |
| 17-1 | For many spiral galaxies, the winding of their spiral arms is correlated to the size of a central bulge | 548 |
| 17-2 | Explosions create flocculent spirals, and waves create grand-design spirals | 550 |
| 17-3 | Bars of stars run through the central bulges of barred spiral galaxies, and some disk galaxies, the lenticulars, lack spiral arms | 554 |
| 17-4 | Elliptical galaxies display a wide variety of sizes and masses | 555 |

| | | | |
|--|-----|--|-----|
| 17-5 Galaxies without global structure are called irregular | 556 | CHAPTER 19 Cosmology | 601 |
| 17-6 Hubble presented spiral and elliptical galaxies in a tuning fork-shaped diagram | 557 | THE BIG BANG | 602 |
| 17-7 Galaxies built up in size over time | 558 | 19-1 General relativity predicts an expanding (or contracting) universe | 602 |
| CLUSTERS AND SUPERCLUSTERS | 559 | 19-2 The expansion of the universe creates a Dopplerlike redshift | 602 |
| 17-8 Galaxies exist in clusters, which are clustered in larger clumps called superclusters | 559 | 19-3 The Hubble constant is related to the age of the universe | 603 |
| 17-9 Clusters of galaxies may appear densely or sparsely populated and regular or irregular in shape | 561 | AN ASTRONOMER'S TOOLBOX 19-1 H_0 and the Age of the Universe | 604 |
| 17-10 Galaxies in a cluster can collide and combine | 562 | 19-4 Remnants of the Big Bang have been detected | 604 |
| 17-11 Dark matter helps hold together individual galaxies and clusters of galaxies | 567 | 19-5 The universe has two symmetries— <i>isotropy</i> and <i>homogeneity</i> | 606 |
| SUPERCLUSTERS IN MOTION | 569 | A BRIEF HISTORY OF SPACETIME, MATTER, ENERGY, AND EVERYTHING | 608 |
| 17-12 The redshifts of superclusters indicate that the universe is indeed expanding | 569 | 19-6 All physical forces in nature were initially unified | 608 |
| GUIDED DISCOVERY The Tully–Fisher Relation and Other Distance-Measuring Techniques | 571 | 19-7 Equations explain the evolution of the universe, even before matter and energy, as we know them, existed | 609 |
| 17-13 Astronomers are looking back to a time when galaxies were first forming | 572 | 19-8 Homogeneity and isotropy are results of inflation | 610 |
| AN ASTRONOMER'S TOOLBOX 17-1 The Hubble–Lemaître Law | 573 | 19-9 During the first second, most of the matter and antimatter in the universe annihilated each other | 611 |
| GUIDED DISCOVERY The Expanding Universe | 574 | 19-10 The universe changed from being controlled by radiation to being controlled by matter | 612 |
| 17-14 Frontiers yet to be discovered | 574 | 19-11 Galaxies formed from huge clouds of primordial gas | 615 |
| SUMMARY OF KEY IDEAS | 575 | 19-12 Star formation activity determines a galaxy's initial structure | 619 |
| WHAT IF... The Solar System Were Located Closer to the Center of the Galaxy? | 579 | THE FATE OF THE UNIVERSE | 620 |
| MEET THE DISCOVERERS Dr. Kartik Sheth | 580 | 19-13 The average density of matter is one factor that determines the future of the universe | 620 |
| CHAPTER 18 Quasars and Other Active Galaxies | 583 | 19-14 The overall shape of spacetime affects the future of the universe | 621 |
| QUASARS | 584 | 19-15 Dark energy is causing the universe to accelerate outward | 622 |
| 18-1 Quasars look like stars but have huge redshifts | 585 | GUIDED DISCOVERY Superstring Theory and M-Theory | 625 |
| 18-2 A quasar emits a huge amount of energy from a small volume | 586 | 19-16 Frontiers yet to be discovered | 626 |
| OTHER ACTIVE GALAXIES | 588 | Summary of Key Ideas | 626 |
| 18-3 Active galaxies can be either spiral or elliptical | 588 | MEET THE DISCOVERERS Dr. Yun Wang | 630 |
| SUPERMASSIVE ENGINES | 590 | CHAPTER 20 Astrobiology | 633 |
| 18-4 Supermassive black holes exist at the centers of most galaxies | 590 | 20-1 Astrobiology connects the cosmos and the origins of life | 634 |
| 18-5 Jets of protons and electrons ejected from around black holes explain quasars, Seyfert galaxies, radio galaxies, double-radio sources, and BL Lacertae objects | 593 | 20-2 The existence of life depends on chemical and physical properties of matter | 635 |
| 18-6 Gravity focuses light from quasars | 596 | 20-3 Evidence is mounting that life might exist elsewhere in our solar system | 638 |
| 18-7 Fast radio bursts | 597 | 20-4 Searches for advanced civilizations try to detect their radio signals | 638 |
| 18-8 Frontiers yet to be discovered | 597 | | |
| Summary of Key Ideas | 597 | | |

XII CONTENTS

20-5 The Drake equation: How many civilizations are likely to exist in the Milky Way? 641

20-6 Humans have been sending signals into space for more than a century 642

20-7 Frontiers yet to be discovered 643

Summary of Key Ideas 644

MEET THE DISCOVERERS *Dr. Magdalena Osburn* 646

APPENDICES

A Powers-of-Ten Notation A-1

B Guidelines for Solving Math Problems and Reading Graphs A-1

C Key Formulas A-4

D Temperature Scales A-5

E Data Tables A-6

F Periodic Table of the Elements A-16

G Largest Optical Telescopes in the World A-17

H Buying a Telescope A-19

Glossary G-1

Answers to Selected Questions ANS-1

Index I-1

PREFACE

OPEN THE DOOR TO DISCOVERY

To confine our attention to terrestrial matters would be to limit the human spirit.

—STEPHEN HAWKING

Learning is a complex process of acquiring new information, comparing it to what we think we know, learning how to unlearn incorrect information, finding places for new facts in our memories, and finding ways of recalling them, among other things. Based on decades of teaching and of studying how people learn, *Discovering the Universe* incorporates a wide variety of insights in many places that help students both learn (currently accepted information) and unlearn (misconceptions about the cosmos). Indeed, *Discovering the Universe* has all the elements needed to learn quickly and efficiently, and all at a student-friendly level.

The eleventh edition of *Discovering the Universe* includes: many brand-new images, including some of Pluto, Ceres, and Jupiter; updates on the search for life on other worlds; and exciting results of gravitational wave and neutrino observations, among many other things. The book also provides coverage of many recent astronomical discoveries, all presented at a level accessible and insightful to students. This edition includes new pedagogical features to engage and challenge students, along with additional examples of the familiar features from previous editions.

NEW! Exoplanets Chapter expands the coverage of our rapidly developing knowledge and understanding of exoplanets (planets orbiting stars other than the Sun).

NEW! Meet the Discoverers interviews working astronomers across the field to provide insight into the process of doing science, as well as the inspiration that drives the people who do that work. This material will help students understand astronomy as an active, relevant, and vibrant discipline.

MEET THE DISCOVERERS

Dr. John Johnson is a Professor of Astronomy at Harvard University, where he leads the ExoLab, specializing in the detection and characterization of exoplanets.



(Michael Wong)

What Do You Think? questions at the beginning of each chapter invite students to examine and challenge their current understanding of astronomical phenomena. Tags within the text sections indicate where students can look to find the relevant information. **What Did You Think?** answers at the end of each chapter ask students to revisit their initial answers and reconcile them with what they have learned over the course of the chapter.

WHAT DO YOU THINK?

- | | |
|---|--|
| <p>1 What is light?</p> <p>2 Which type of electromagnetic radiation is most dangerous to life?</p> <p>3 What is the main purpose of a telescope?</p> <p>4 Why do research telescopes that collect electromagnetic radiation use mirrors, rather than lenses, to collect light?</p> | <p>5 Why do stars twinkle?</p> <p>6 What are cosmic rays? Where do they come from?</p> |
|---|--|

Answers to these questions appear in the text beside the corresponding numbers in the margins and at the end of the chapter.

3-3 Einstein showed that light sometimes behaves as particles that carry energy

1 By 1905, scientists were comfortable with the wave nature of light. However, in that year, Albert Einstein (1879–1955) threw a monkey wrench into that theory when he proposed that light is composed of particles that have wave properties, creating what is now called the *wave-particle duality*. He used this idea to explain the *photoelectric effect*. Physicists knew that electrons are bound onto a metal's surface by electric forces and that it takes energy to overcome those forces. Shorter wavelengths of light can knock some electrons off the surfaces of metals, while longer wavelengths of light cannot, no matter how intense the beam of long-wavelength light. Because some colors (or, equivalently, wavelengths) can remove the electrons and others cannot, the electrons must receive different amounts of

What If... questions inspire student curiosity and invite them to think critically about the way our universe works.

WHAT IF...

Stars actually twinkled?

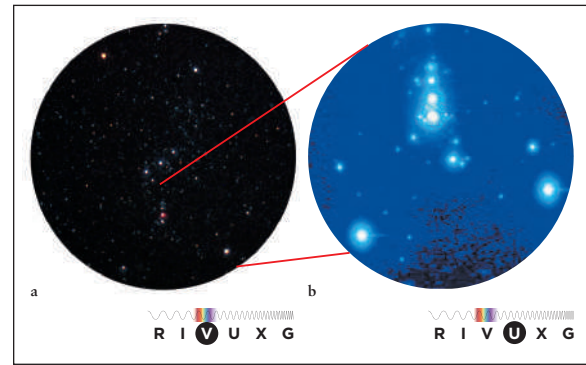
Stars appear to significantly change their brightness (twinkle) in fractions of a second. If they actually did vary in brightness as much as we see them vary, they would do so by changing size—bigger is brighter. If such expansion and contraction occurred, the rapid motion of their gases would cause stars to blow apart in a matter of seconds.

Guided Discovery goes in-depth on challenging astronomical concepts to help students gain a conceptual understanding through thoughtful analogies and useful perspectives from the history of science.

An Astronomer's Almanac, a dynamic timeline that relates discoveries in astronomy to other historical events, opens each of the four Parts of the text. These almanacs provide strong context for the information presented.

An Astronomer's Toolbox introduces some of the algebraic equations used in astronomy. Most of the material in the book is descriptive, so essential equations are set off in numbered boxes to maintain the flow of the material and to allow students and instructors to focus on the right level of quantitative material for their course. The toolboxes also contain worked examples, additional explanations, and practice doing calculations; answers are given at the end of the book. All the equations are summarized in Appendix C.

Wavelength Indicators included with photographic images show whether an image was made with radio waves (R), infrared radiation (I), visible light (V), ultraviolet light (U), X-rays (X), or gamma rays (G).



(a: peresanz/iStock/Getty Images; b: NASA/MSX/Johns Hopkins University Applied Physics Laboratory)

Margin Questions give students the opportunity to reinforce a variety of important concepts they have read in just the previous page or two. This can help solidify concepts that are challenging, easy to confuse, or that are associated with common misconceptions.

Margin Question 3-3
Which has more energy, an infrared photon or an ultraviolet photon?

In This Chapter items provide the most important learning goals of each chapter. It helps orient students to the upcoming topics and provides a checklist for their reading of the chapter.

Insight Into Science boxes provide insights into how science works, why it works, what scientists do, and how science protects itself from pseudoscientific claims. These boxes provide important information that applies to all realms of science and, as such, takes students beyond just the factual information about astronomy.

Insight Into Science

Research Requires Patience Seeing conditions—indeed, most observing situations in science—are rarely ideal. Besides such natural phenomena, which are beyond their control, scientists must also contend with equipment failures, late deliveries of parts, and design flaws. Furthermore, because travel time is so long, some missions (like the robotic spacecraft roving on Mars or the New Horizons voyage to Pluto and the Kuiper belt) take years or even decades to complete.

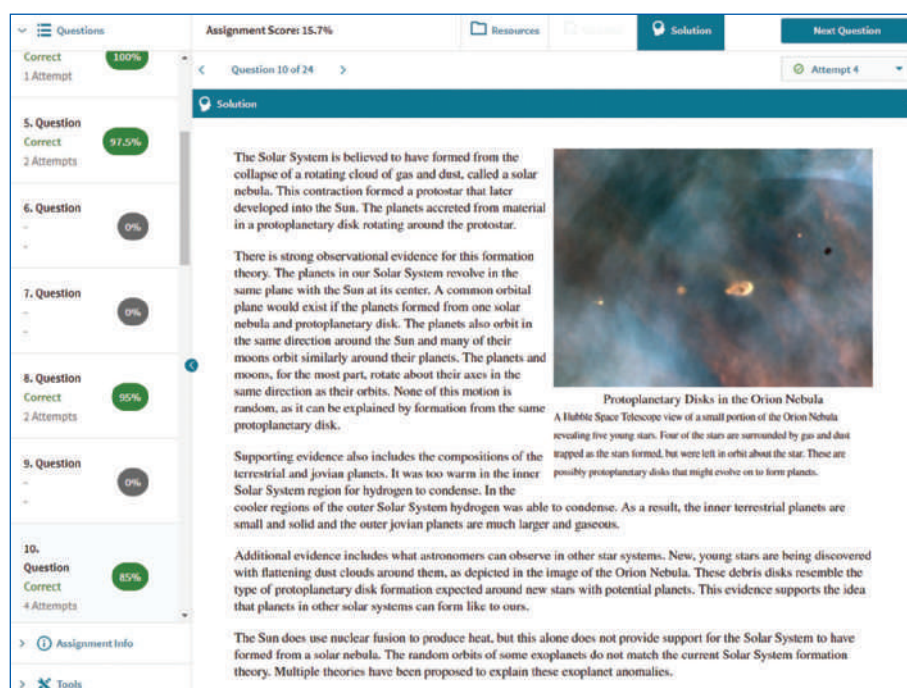
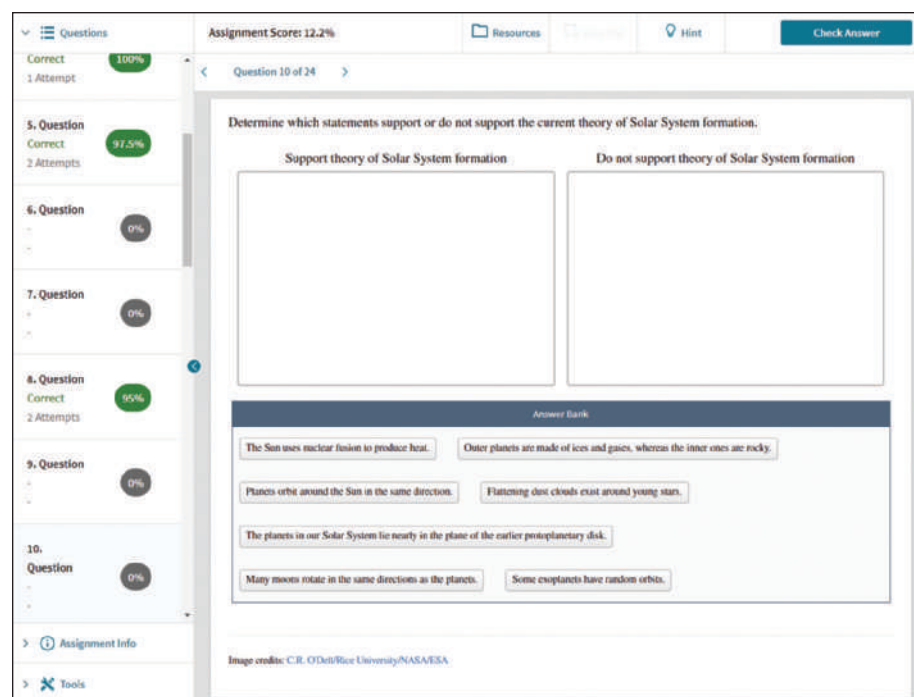
Starry Night™ Explorations in the end-of-chapter questions ask students to be astronomers themselves by providing activities to complete within the robust, interactive *Starry Night™* observational software.

of LearningCurve adaptive quizzing. In the Sapling homework, every question includes hints, targeted, answer-specific feedback, and fully worked-out solutions to guide students through their progress toward understanding.

ONLINE HOMEWORK AND MEDIA

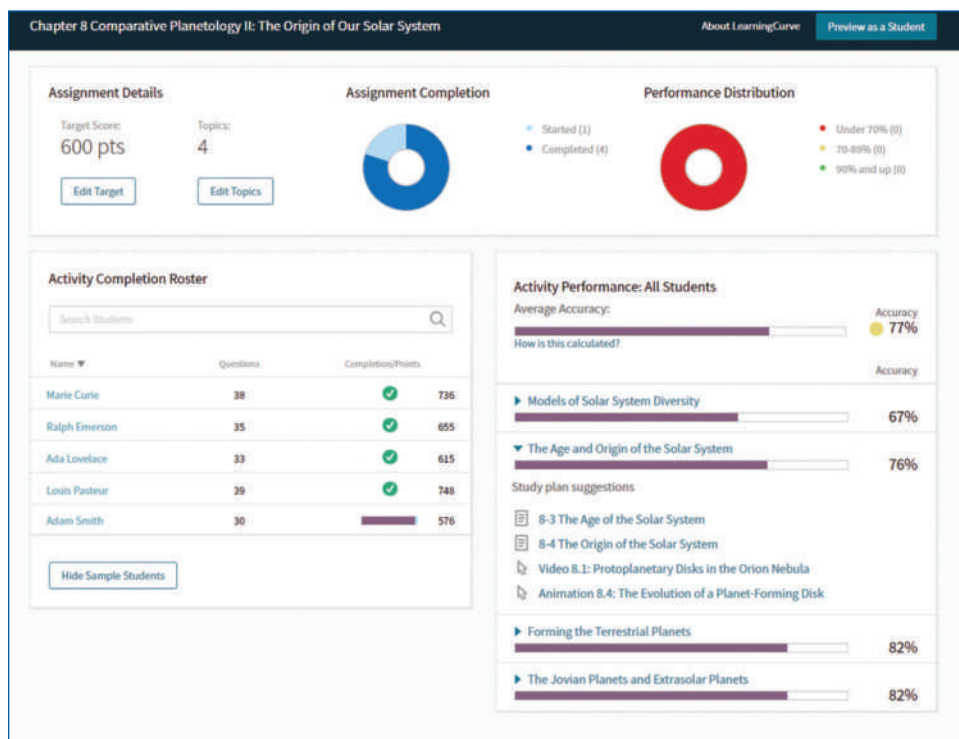


Sapling Plus for *Discovering the Universe* combines the rigor of Sapling homework with the formative power



LearningCurve adaptive quizzing provides material at different difficulty levels and topics based on student performance. Students work to achieve a target score, allowing highly prepared students to complete the activity promptly, and providing students

unfamiliar with the material the necessary time to practice. The student and instructor dashboards provide the accuracy of student responses for each topic, giving insight into important topics to review in class or study.



The mobile-accessible e-book included with every course contains embedded animations to augment the striking visuals found in the text, as well as many tools for studying, such as shareable highlighting, note-taking, and flashcards.



Achieve Read & Practice marries Macmillan Learning's mobile-accessible e-book with the acclaimed LearningCurve adaptive quizzing. It is an easy-to-use yet exceptionally powerful teaching and learning option that streamlines the process of increasing student engagement and understanding. Instructors can assign reading simply, students can complete assignments on any device, and the cost is significantly less than that of a printed book.

With Achieve Read & Practice:

- Instructors can arrange and assign chapters and sections from the e-book in any sequence they prefer.
- Assignments come with LearningCurve quizzes offering individualized question sets, feedback, and e-book

references that adapt to correct and incorrect answers. If students struggle with a particular topic, they are encouraged to reread the material and answer a few short additional questions.

- The Read & Practice gradebook tracks student performance individually and for the whole class, helping instructors shape their lectures and address underperforming topics.

STARRY NIGHT™

Starry Night™ is a brilliantly realistic planetarium software package. It is designed for easy use by anyone with an interest in the night sky. See the sky from anywhere on Earth or lift off and visit any solar system body or any location up to 20,000 light-years away. A download code for *Starry Night™* is available with the text upon request.

INSTRUCTORS RESOURCES

The instructor's resources for *Discovering the Universe* are all available for download from SaplingPlus, as well as from the Macmillan Learning catalog site.

The **Test Bank** offers more than 3,500 multiple-choice questions that are section-referenced, available in

editable Microsoft Word documents or Diploma files for quick exam creation.

The **Instructor's Manual** accompanying the text provides instructors with a summary and table of contents of each chapter, pedagogical advice on how to teach the chapter, additional questions for in-class discussion, and the answers to book problems, all in one place.

Lecture Slides and Images in PowerPoint allow instructors to tailor their lectures to suit their own needs using images and notes from the textbook, preorganized into slides.

Clicker Questions can be used as lecture launchers with or without a classroom response system such as iClicker. Each chapter includes questions relating to figures from the text and common misconceptions, as well as writing questions for instructors who would like to add a writing or class discussion element to their lectures.

ACKNOWLEDGMENTS

I am deeply grateful to the astronomers and teachers who have reviewed the manuscript of this and previous editions. This is a stronger and better book because of their conscientious efforts:

Miah M. Adel, *University of Arkansas, Pine Bluff*
 Steven Ball, *LeTourneau University*
 Kirsten R. Bernabee, *Idaho State University*
 Bruce W. Bridenbecker, *Copper Mountain College*
 Eric Centauri, *University of Tulsa*
 Larry A. Ciupik, *Indiana University Northwest*
 Michael K. Durand, *California State University, Dominguez Hills*
 Gregory J. Falabella, *Wagner College*
 Tim Farris, *Volunteer State Community College*
 Rica Sirbaugh French, *MiraCosta College*
 Wayne K. Guinn, *Lon Morris College*
 Richard Ignace, *East Tennessee State University*
 Alex Ignatiev, *University of Houston*
 Mahmoud Khalili, *Northeastern Illinois University*
 Kevin Krisciunas, *Texas A&M University*
 Peter Lanagan, *College of Southern Nevada*
 Shawn T. Langan, *University of Nebraska, Lincoln*
 James Lauroesch, *University of Louisville*
 Lauren Likkel, *University of Wisconsin, Eau Claire*
 Jane H. MacGibbon, *University of North Florida*
 Melissa A. Morris, *Arizona State University*
 Douglas Nagy, *Ursinus College*
 Christopher Palma, *Pennsylvania State University*
 Billy L. Quarles, *University of Texas, Arlington*
 Susan R. Rolke, *Franklin Pierce University*
 Richard Ross, *Rock Valley College*
 Mehmet Alper Sahiner, *Seton Hall University*

Kelli Corrado Spangler, *Montgomery County Community College*
 Philip T. Spickler, *Bridgewater College*
 Aaron R. Warren, *Purdue University North Central*
 Lee C. Widmer, *Xavier University*

I would also like to thank the many people whose advice on previous editions has had an ongoing influence:

John Anderson, *University of North Florida*
 Kurt S. J. Anderson, *New Mexico State University*
 Gordan Baird, *University of Arizona*
 Nadine G. Barlow, *Northern Arizona University*
 Henry E. Bass, *University of Mississippi*
 J. David Batchelor, *Community College of Southern Nevada*
 Jill Bechtold, *University of Arizona*
 Peter A. Becker, *George Mason University*
 Ralph L. Benbow, *Northern Illinois University*
 John Bieging, *University of Arizona*
 Greg Black, *University of Virginia*
 John C. (Jack) Brandt, *University of New Mexico*
 James S. Brooks, *Florida State University*
 John W. Burns, *Mt. San Antonio College*
 Gene Byrd, *University of Alabama*
 Eugene R. Capriotti, *Michigan State University*
 Eric D. Carlson, *Wake Forest University*
 Jennifer L. Cash, *South Carolina State University*
 Michael W. Castelaz, *Pisgah Astronomical Research Institute*
 Gerald Cecil, *University of North Carolina*
 David S. Chandler, *Porterville College*
 David Chernoff, *Cornell University*
 Erik N. Christensen, *South Florida Community College*
 Tom Christensen, *University of Colorado, Colorado Springs*
 Chris Clemens, *University of North Carolina*
 Christine Clement, *University of Toronto*
 Halden Cohn, *Indiana University*
 John Cowan, *University of Oklahoma*
 Antoinette Cowie, *University of Hawaii*
 Charles Curry, *University of Waterloo*
 James J. D'Amario, *Harford Community College*
 Purnas Das, *Purdue University*
 Peter Dawson, *Trent University*
 John M. Dickey, *University of Minnesota, Twin Cities*
 John D. Eggert, *Daytona Beach Community College*
 Stephen S. Eikenberry, *University of Florida*
 Bernd Enders, *College of Marin*
 Andrew Favia, *University of Maine*
 Rica French, *Mira Costa College*
 Robert Frostick, *West Virginia State College*
 Martin Gaskell, *University of Nebraska*
 Richard E. Griffiths, *Carnegie Mellon University*

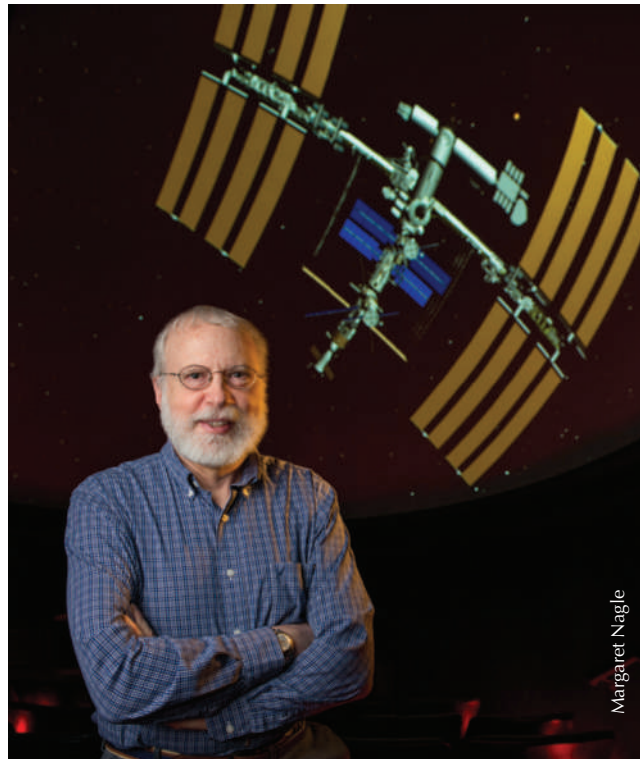
Bruce Gronich, *University of Texas, El Paso*
 Siegbert Hagmann, *Kansas State University*
 Thomasanna C. Hail, *University of Mississippi*
 Javier Hasbun, *University of West Georgia*
 David Hedin, *Northern Illinois University*
 Chuck Higgins, *Pennsylvania State University*
 Scott S. Hildreth, *Chabot College*
 Thomas Hockey, *University of Northern Iowa*
 Mark Hollabaugh, *Normandale Community College*
 J. Christopher Hunt, *Prince George's Community College*
 James L. Hunt, *University of Guelph*
 Nathan Israeloff, *Northeastern College*
 Francine Jackson, *Framingham State College*
 Fred Jacquin, *Onondaga Community College*
 Kenneth Janes, *Boston University*
 Katie Jore, *University of Wisconsin–Steven's Point*
 William C. Keel, *University of Alabama*
 William Keller, *St. Petersburg Junior College*
 Marvin D. Kemple, *Indiana University–Purdue University Indianapolis*
 Pushpa Khare, *University of Illinois at Chicago*
 F. W. Kleinhaus, *Indiana University–Purdue University Indianapolis*
 Agnes Kim, *Georgia College & State University*
 Rob Klinger, *Parkland College*
 H. S. La, *Clayton State University*
 Patrick M. Len, *Cuesta College*
 John Patrick Lestrade, *Mississippi State University*
 C. L. Littler, *University of North Texas*
 M. A. K. Lohdi, *Texas Tech University*
 Michael C. LoPresto, *Henry Ford Community College*
 Phyllis Lugger, *Indiana University*
 R. M. MacQueen, *Rhodes College*
 Robert Manning, *Davidson College*
 Paul Mason, *University of Texas, El Paso*
 P. L. Matheson, *Salt Lake Community College*
 Steve May, *Walla Walla Community College*
 Rahul Mehta, *University of Central Arkansas*
 Ken Menningen, *University of Wisconsin–Steven's Point*
 J. Scott Miller, *University of Louisville*
 Scott Miller, *Pennsylvania State University*
 L. D. Mitchell, *Cambria County Area Community College*
 J. Ward Moody, *Brigham Young University*
 Siobahn M. Morgan, *University of Northern Iowa*
 Steven Mutz, *Scottsdale Community College*
 Charles Nelson, *Drake University*
 Gerald H. Newsom, *Ohio State University*
 Bob O'Connell, *College of the Redwoods*
 William C. Oelfke, *Valencia Community College*
 Richard P. Olenick, *University of Dallas*
 John P. Oliver, *University of Florida*
 Ron Olowin, *St. Mary's College of California*
 Melvyn Jay Oremland, *Pace University*

Jerome A. Orosz, *San Diego State University*
 David Patton, *Trent University*
 Jon Pedicino, *College of the Redwoods*
 Sidney Perkwitz, *Emory University*
 Lawrence Pinsky, *University of Houston*
 Eric Preston, *Indiana State University*
 David D. Reid, *Wayne State University*
 Adam W. Rengstorf, *Indiana University*
 James A. Roberts, *University of North Texas*
 Henry Robinson, *Montgomery College*
 Dwight P. Russell, *University of Texas, El Paso*
 Barbara Ryden, *Ohio State University*
 Itai Seggev, *University of Mississippi*
 Larry Sessions, *Metropolitan State University*
 C. Ian Short, *Florida Atlantic University*
 John D. Silva, *University of Massachusetts at Dartmouth*
 Michael L. Sitko, *University of Cincinnati*
 Earl F. Skelton, *University of California at Berkeley*
 George F. Smoot, *University of California at Berkeley*
 Alex G. Smith, *University of Florida*
 Jack Sulentic, *University of Alabama*
 David Sturm, *University of Maine, Orono*
 Paula Szkody, *University of Washington*
 Michael T. Vaughan, *Northeastern University*
 Andreas Veh, *Kenai Peninsula College*
 John Wallin, *George Mason University*
 William F. Welsh, *San Diego State University*
 R. M. Williamon, *Emory University*
 Gerard Williger, *University of Louisville*
 J. Wayne Wooten, *Pensacola Junior College*
 Edward L. (Ned) Wright, *University of California at Los Angeles*
 Jeff S. Wright, *Elon College*
 Nicolle E. B. Zellner, *Rensselaer Polytechnic Institute*

I would like to add my special thanks to the wonderfully supportive staff at W. H. Freeman and Company who make the revision process so enjoyable. Among others, these people include Lori Stover, Meg Rosenberg, Kevin Davidson, Kerry O'Shaughnessy, Vicky Garvey, Brittani Murphy, Sheena Goldstein, Kerri Wilson, Brittani Morgan Grimes, and Natasha Wolfe. Thanks also go to my copy-editor and indexer, Louise Ketz. Thank you to Marcel W. Bergman, T. Alan Clark, and William J. F. Wilson for their work on the *Starry Night*[™] material. Warm thanks also to David Sturm, University of Maine, Orono, for his help in collecting current data on objects in the solar system; to my former graduate student, Andrej Favia, for his expert work on identifying, categorizing, and addressing misconceptions about astronomy; to my UM astronomy colleague David Batuski; and to my wife, Sue, for her patience and support while preparing this book.

Neil F. Comins
 galaxy@maine.edu

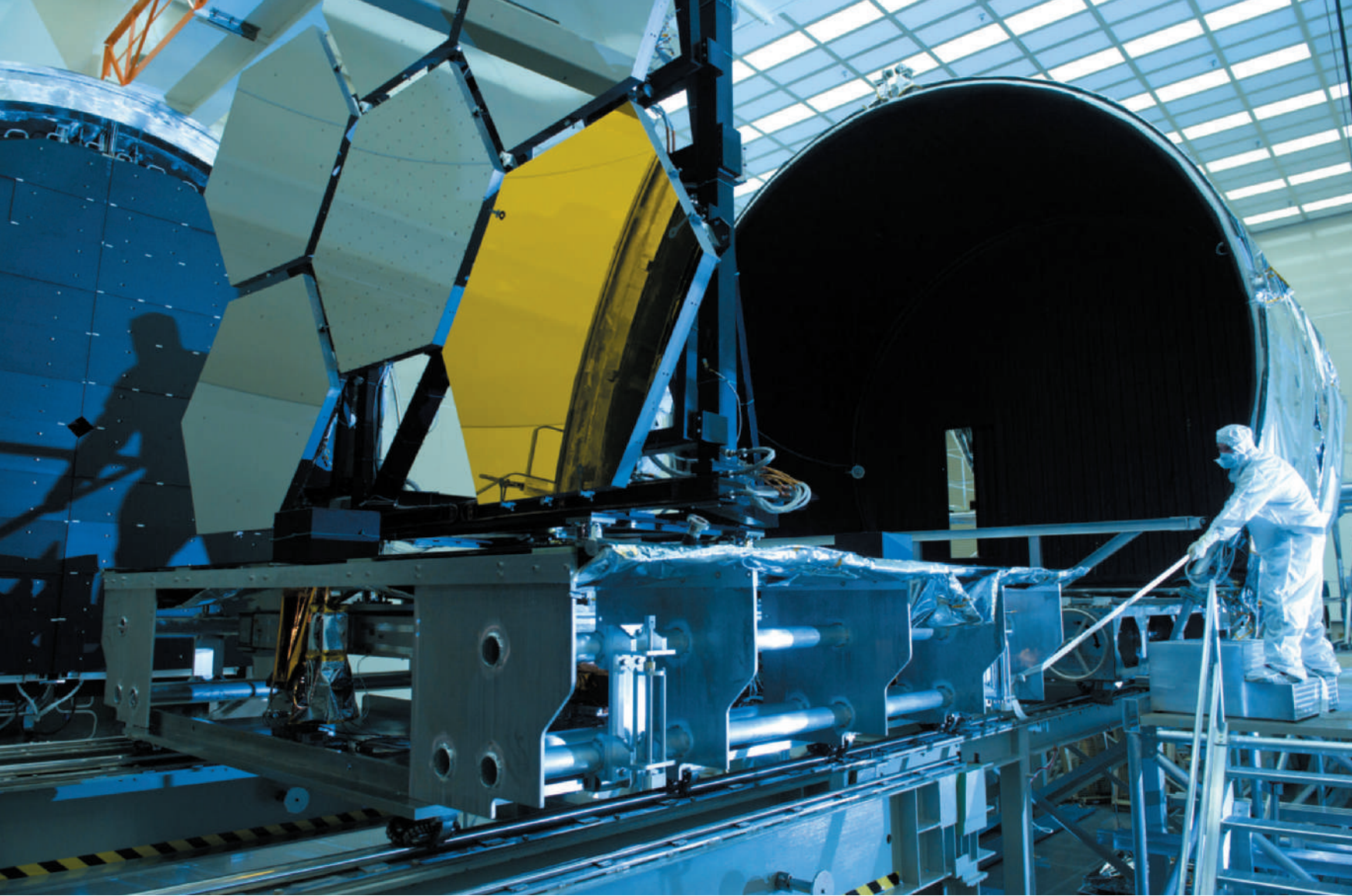
ABOUT THE AUTHOR



Professor Neil F. Comins is on the faculty of the University of Maine. Born in 1951 in New York City, he grew up in New York and New England. He earned a bachelor's degree in engineering physics at Cornell University, a master's degree in physics at the University of Maryland, and a Ph.D. in astrophysics from University College, Cardiff, Wales, under the guidance of Bernard F. Schutz. Dr. Comins's work for his doctorate, on general relativity, was cited in Subramanyan Chandrasekhar's Nobel laureate speech. He has done theoretical and experimental research in general relativity, optical and radio observational astronomy, computer simulations of galaxy evolution, and science education. The fourth edition of *Discovering the Universe* was the first book in this series that Dr. Comins wrote, having taken over following the death of William Kaufmann in 1994. He is also the author of five trade books, *What If the Moon*

Didn't Exist?, *Heavenly Errors*, *The Hazards of Space Travel*, *What If the Earth Had Two Moons?*, and *The Traveler's Guide to Space*. Worlds envisioned in *What If the Moon Didn't Exist?* have been made into planetarium shows, been excerpted for television and radio, and made into Minecraft worlds. The title chapter was also the theme for the Mitsubishi Pavilion at the World Expo 2005 in Aichi, Japan, and is presently a show at the Japanese resort, Huis Ten Bosch. *Heavenly Errors* explores misconceptions people have about astronomy, why such misconceptions are so common, and how to correct them. Dr. Comins has appeared on numerous television and radio shows and gives many public talks. Although he has jumped out of airplanes while in the military, today his activities are a little more sedate: He is a licensed pilot and avid sailor, having once competed against Prince Philip, Duke of Edinburgh.

this page left intentionally blank



Telescopes enhance our views of the cosmos. (NASA/MSFC/Emmett Given)



PART I | UNDERSTANDING THE SCIENCE OF ASTRONOMY

AN ASTRONOMER'S ALMANAC



2136 B.C.E. Chinese astronomers record solar eclipse. (Dr. Mario Motta)

ca. 270 B.C.E.

Aristarchus of Samos proposes heliocentric cosmology.

1512-1543

Nicolas Copernicus proposes heliocentric cosmology in his *Commentariolus* and *De revolutionibus orbium coelestium*.



1715 Edmond Halley calculates shadow path of a solar eclipse over Earth's surface. (NASA/SSPL/Getty Images)

1766 Henry Cavendish discovers hydrogen.

1589-1609

Galileo Galilei proposes that all objects fall with the same acceleration, independent of their masses; builds his first telescope, a refractor.

European Renaissance

586 B.C.E.

Thales of Miletus predicts solar eclipse.

350 B.C.E. Aristotle proposes spherical Earth, geocentric cosmology.

1576-1601

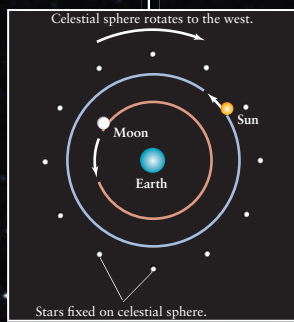
Tycho Brahe makes precise observations of stars and planets.

1609-1610

Johannes Kepler publishes his three laws of planetary motion.

1800-1803

William Herschel discovers infrared radiation from the Sun. Thomas Young demonstrates wave nature of light. John Dalton proposes that matter is composed of atoms of different masses.



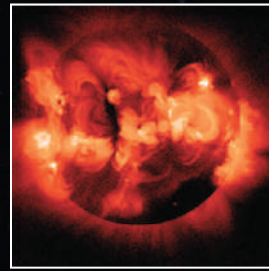
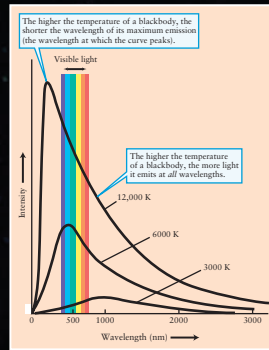
ca. A.D. 125 Claudius Ptolemy refines and details geocentric cosmology in his *Almagest*.



1665-1704 Isaac Newton deduces gravitational force from the orbit of the Moon; builds first reflecting telescope; proves that the planets obey Kepler's laws because they move under the influence of the gravitational force; and publishes compendium on light, *Opticks*. (Photo12/Ann Ronan Picture Library/Alamy)

DISCOVERING ASTRONOMY

1871-1873 Dimitri Mendeleev develops periodic table of the elements. Henry Draper develops spectroscopy. James Clerk Maxwell asserts that light is an electromagnetic phenomenon.



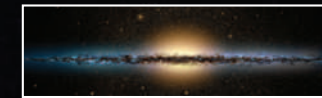
1942-1949 J. S. Hey detects radio waves from the Sun. First astronomical telescope launched into space. Herbert Friedman detects X-rays from the Sun. 200-in. optical reflecting telescope begins operation on Mt. Palomar, California. (Lockheed-Martin Solar & Astrophysics Laboratory, the National Astronomical Observatory of Japan, the University of Tokyo, NASA & ISAS)

1847 Maria Mitchell observed a comet, now called "Miss Mitchell's Comet," through a telescope.

1900 Max Planck explains blackbody radiation. Paul Villard discovers gamma rays.

1885-1888 Johann Balmer expresses spectral lines of hydrogen mathematically. Heinrich Hertz detects radio waves.

1930-1934 Karl Jansky builds first radio telescope. James Chadwick discovers the neutron. Bernhard Schmidt builds his Schmidt optical reflecting telescope.



1990-1996 Hubble Space Telescope launched. Keck 10-m optical/infrared telescopes begin operation at Mauna Kea, Hawaii. SOHO solar observatory launched. (Chris Butler/Science Source)

Industrial Revolution

1975 First charge-coupled device (CCD) astronomical observations.

2004-present Two rovers travel on Mars, detectors search for gravitational radiation.

Information Age



1895-1897 Wilhelm Roentgen discovers X-rays. Joseph Thomson detects the electron. Yerkes 40-in. optical refracting telescope completed. (ALAN SOLOMON/Tribune News Service/LAKE GENEVA/WI/USA/Newscom)

1963-1967 Largest single-dish radio telescope, 300 m across, begins operation at Arecibo, Puerto Rico. First Very Long Baseline Interferometer (VLBI) images.

1999 Chandra X-ray Telescope launched.



1840-1849 J. W. Draper invents astronomical photography; takes first photographs of the Moon. Christian Doppler proposes that wavelength is affected by motion. Lord Rosse completes 60-in. reflecting telescope at Birr Castle in Ireland. Armand Fizeau and Jean-Bernard Foucault measure speed of light accurately. (ClawsAndPaws/iStock/Getty Images)



1913 Niels Bohr proposes quantum theory of the atom. (Roman Sigaev/Shutterstock)

1980 Very Large Array (VLA) radio observatory completed, Socorro, New Mexico.

2013 *Voyager 1* is first spacecraft to leave the solar system.

this page left intentionally blank



The night sky is stunning when viewed in dark, pollution-free environments. (Westend61/Getty Images)



CHAPTER

1

Discovering the Night Sky

WHAT DO YOU THINK?

- 1 Is the North Star—Polaris—the brightest star in the night sky?
- 2 What do astronomers define as constellations?
- 3 What causes the seasons?
- 4 When is Earth closest to the Sun?
- 5 How many zodiac constellations are there?
- 6 Does the Moon have a dark side that we never see from Earth?
- 7 Is the Moon ever visible during the daytime?
- 8 What causes lunar and solar eclipses?

Answers to these questions appear in the text beside the corresponding numbers in the margins and at the end of the chapter.

You are studying astronomy at an extraordinary time, as our understanding of the cosmos (or the *universe*) and how it evolves grows as never before. That is due, in large measure, to the immense light-gathering power and sensitivity of modern telescopes, as well as the recent development of telescopes that can detect gravitational radiation (minuscule vibrations of space-time). Both types of telescopes enable us to test mathematical theories that describe many aspects of the cosmos, as well as to discover totally unexpected phenomena, such as the fact that the universe is expanding faster every day.

Current telescope technology makes it possible for astronomers to observe objects and events that were completely invisible to us just a few years ago. For example, we can now see so far away—and therefore so far into the past—that we see the first stars and the first galaxies as they just began forming more than 13½ billion years ago. We could not see these objects even two decades ago, and likewise, it took just 21 years for astronomers to discover 1000 planets orbiting nearby stars, a feat that would have been impossible 30 years ago. After 25 years of searching, we have cataloged over 3700 of these worlds.

Telescopes are not the only means by which we are deepening our understanding of what lies beyond Earth’s atmosphere. We have also begun the process of physically exploring our neighborhood in space. In just the past half century, humans have walked on the Moon; space probes have roamed over parts of Mars, dug into its rocks and soil, and blasted its surface with laser beams. Other probes have crashed into one comet; brought back debris from another one; landed on an asteroid and on Saturn’s murky moon Titan; traveled through the shimmering rings of Saturn; discovered active volcanoes and barren ice fields on the moons of Jupiter; and, some have even departed from the realm of the planets in our solar system, to mention just a few accomplishments. (The solar system is comprised of the Sun and every object that orbits it.) We are also witnessing the dawn of space tourism, with people buying trips to the International Space Station.

In the best locations, the night sky is truly breathtaking (Figure 1-1a). Even if you cannot see the thousands of stars visible in clear locations (see Figure 1-1b), software such as *Starry Night™* can show them to you. The night sky can draw you out of yourself, inviting you to understand what is happening beyond Earth and inspiring you to think about our place in the universe.

Until the past few centuries, the explanations people found for what they saw in the sky were based on beliefs that had to be accepted on faith—there was no way to test ideas of what stars are, or whether the Moon really has liquid water oceans (as was believed back then but is not true), or how the planets move, or why the Sun shines. Times have changed. We are fortunate to be



a



b

RIVUXG

FIGURE 1-1 The Night Sky Without and With Light Pollution (a) The daytime sky, made by scattering blue sunlight, is a curtain that hides virtually everything behind it. (Can you name two exceptions?) As the Sun sets, places with little smog or light pollution treat viewers to beautiful panoramas of stars that inspire the artist or scientist in many of us. This photograph shows the night sky in Goodwood, Ontario, Canada, during a power outage. (b) This photograph shows the same sky with normal city lighting. (Todd Carlson/SkyNews Magazine)

living in an era when science has answers to many of the questions inspired by the universe.

Beautiful, intriguing, and practical, astronomy and its ongoing process of discovery have something for everyone. This course and this book will help you better understand the universe by sharing what we have learned and are still learning about many of these questions. They will also demonstrate the awesome power of the human mind to reach out, to observe, to explore, and to comprehend. One of the great lessons of modern astronomy is that by gaining, sharing, and passing on

knowledge, we transcend the limitations of our bodies and the brevity of human life.

IN THIS CHAPTER YOU WILL DISCOVER

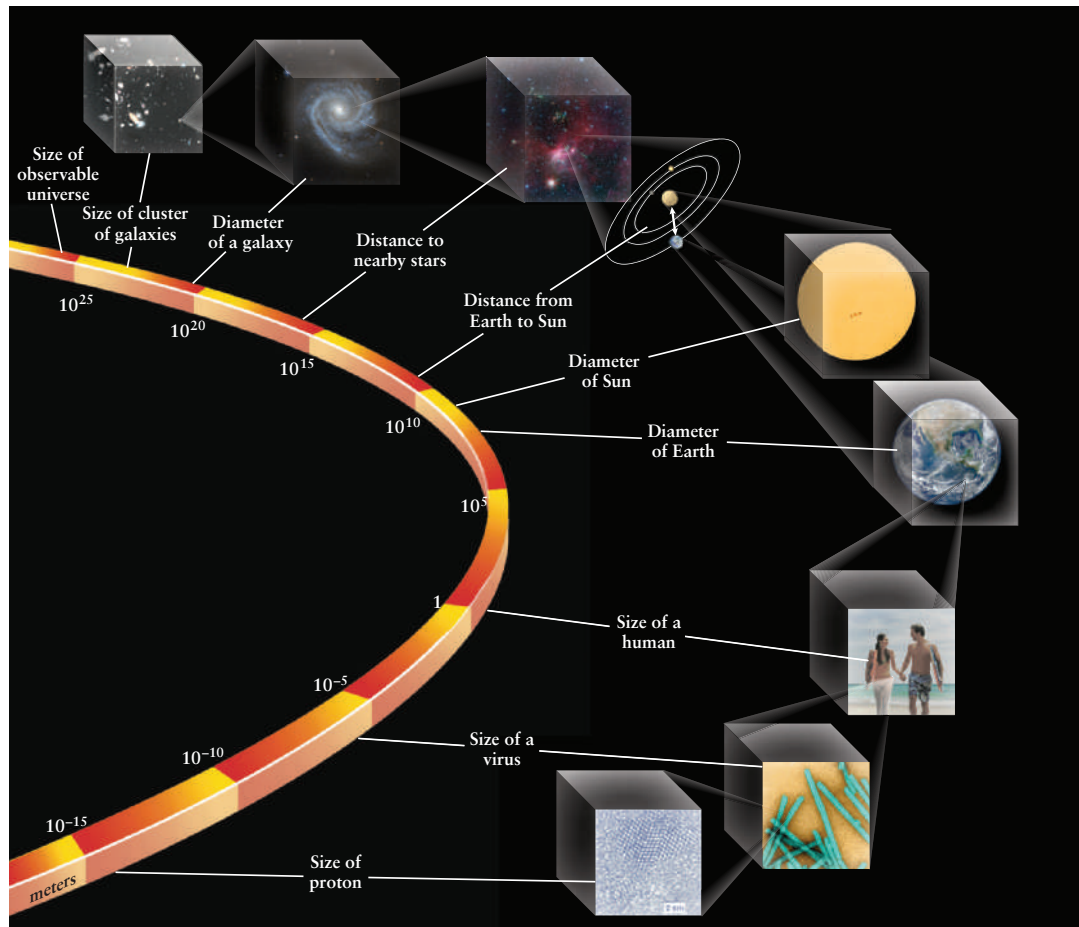
- how astronomers map the night sky to help them locate objects in it
- that Earth's spin on its axis causes day and night
- how Earth's orbit around the Sun combined with the tilt of Earth's axis of rotation relative to its orbit create the seasons
- that the Moon's orbit as seen from Earth creates the phases of the Moon, as well as lunar and solar eclipses
- how the year is defined and how the calendar was developed

SCALES OF THE UNIVERSE

In learning a new field it is often useful to see the “big picture” before exploring the details. For this reason, we begin by surveying the major types of objects in the universe, along with their ranges of size and the scale of distances between them (Figure 1-2).

1-1 Astronomical distances are, well, astronomical

One of the thrills and challenges of studying astronomy is becoming familiar and comfortable with the vast range of sizes that occur in it. In our everyday lives we typically deal with distances ranging from millimeters to thousands of kilometers. (The metric or International System [SI] of units is standard in science and will be used throughout this book; however, we will often provide the equivalent in U.S. customary units.



R I V U X G

ANIMATION 1.1 **FIGURE 1-2 The Scales of the Universe** This curve gives the sizes of objects in meters, ranging from subatomic particles at the bottom to the entire observable universe at the top. Every 0.5 cm up along the arc represents a factor of 10 larger. (Top to bottom: R. Williams and the Hubble Deep Field Team

[STScI] and NASA; ESA/Hubble & NASA; NASA/JPL-Caltech/University of Wisconsin; NASA/SDO/HMI; NASA/NOAA/GSFC/Suomi NPP/VIIRS/Norman Kuring; Jose Luis Pelaez/Getty Images; Lee D. Simon/Science Source; Courtesy of Florian Bahart/University of Mainz)

Appendix E-10 lists conversion factors between these two sets of units.)

A hundredth of a meter or a thousand kilometers are numbers that are easy to visualize and write. In astronomy, we deal with particles as small as a millionth of a billionth of a meter and systems of stars as large as a thousand billion billion kilometers across. Similarly, the speeds of some things, like light, are so high as to be cumbersome if you have to write them out in words each time. **Scientific notation** (Appendix A) makes comparisons easy, telling us how many factors of 10 in size, mass, brightness, distance, and other parameters one object is compared to another.

The size of the universe that we can observe and the range of sizes of the objects in it are truly staggering. Figure 1-2 summarizes the array of sizes from atomic particles up to the diameter of the entire universe visible to us. Unlike linear intervals measured on a ruler, the sizes of objects increase by powers of 10 in equal intervals in this figure; moving up 0.5×10^{-2} m (0.5 cm) along the arc of this figure brings you to objects 10 times larger. Because of this, going from the size of a proton (roughly 10^{-15} m) up to the size of an atom (roughly 10^{-10} m) takes about the same space along the arc as going from the distance between Earth and the Sun to the distance between Earth and the nearby stars.

This wide range of sizes underscores the fact that astronomy *synthesizes* or brings together information from many other fields of science. While we cannot go to the ends of the universe to examine all its components, the light from the universe coming to us, combined with our ever-growing understanding of the laws of nature, provides invaluable insights into how the various components of the cosmos work and how they interact with each other. We will discuss some of the underlying principles of science as we need them.

What, then, have astronomers seen of the universe? **Figure 1-3** presents examples of the types of objects we will explore in this text. An increasing number of planets like Jupiter, rich in hydrogen and helium (Figure 1-3a), as well as rocky planets similar to Earth, are being discovered orbiting other stars. Much smaller pieces of space debris—some of rock and metal called **asteroids** or **meteoroids** (Figure 1-3b), and others of rock and ice called **comets** (Figure 1-3c)—orbit the Sun (Figure 1-3d) and other stars. Vast stores of interstellar gas and dust are found in many galaxies; these “clouds” are often the incubators of new generations of stars (Figure 1-3e). Stars by the millions, billions, or even trillions, often accompanied by interstellar gas and dust, are held together in galaxies by the force of their mutual gravitational attraction (i.e., gravity; Figure 1-3f).

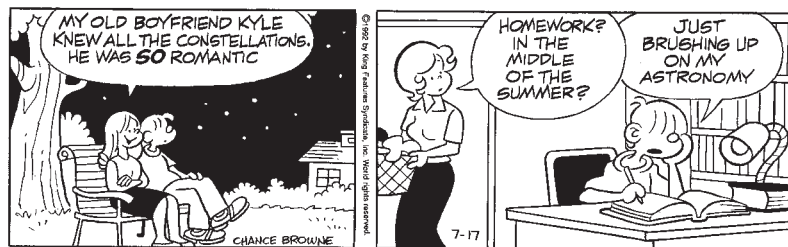
Most galaxies also contain **black holes**, objects with such strong gravitational attraction that nothing can escape from them in the usual sense of how light leaves from the Sun or rockets leave Earth (Figure 1-3g). Groups of galaxies, called clusters, are held together by gravity (Figure 1-3h), and clusters of galaxies are grouped together in superclusters. Huge quantities of intergalactic gas are often found between galaxies (Figure 1-3i).

Every object in astronomy is constantly changing—each has an origin, an active period you might consider as its “life,” and each will have an end. In addition to examining the objects that fill the universe, we will also study the processes that cause them to change. After all is said and done, you will discover that all the matter and energy that astronomers have detected are but the tip of the cosmic iceberg—there is much more in the universe, but astronomers do not yet know its nature!

PATTERNS OF STARS

When you gaze at the sky on a clear night where the air is free of pollution and there is not too much light from cities or other sources, there seem to be millions of stars twinkling overhead. In reality, the unaided human eye can detect only about 6000 stars over the entire sky. At any one time, you can see roughly 3000 stars in dark skies, because only half of the stars are above the *horizon*—the boundary between Earth and the sky. In very smoggy or light-polluted cities, you may see only a tenth of that number or less (see Figure 1-1).

In any event, you probably have noticed patterns of bright stars, each technically called an **asterism**, and you are familiar with some common names for some of them, such as the ladle-shaped Big Dipper and broad-shouldered Orion. These recognizable patterns of stars (**Figure 1-4a**) are informally called *constellations* in everyday conversation. Technically, however, constellations are entire regions of the sky and everything in them (**Figure 1-4b**). In what follows, we will often use the word “constellation” to mean either the asterisms or the regions of the sky. Be careful to consider which version of the word is in use.



(HI & LOIS ©1992 by King Features Syndicate, Inc. World rights reserved)

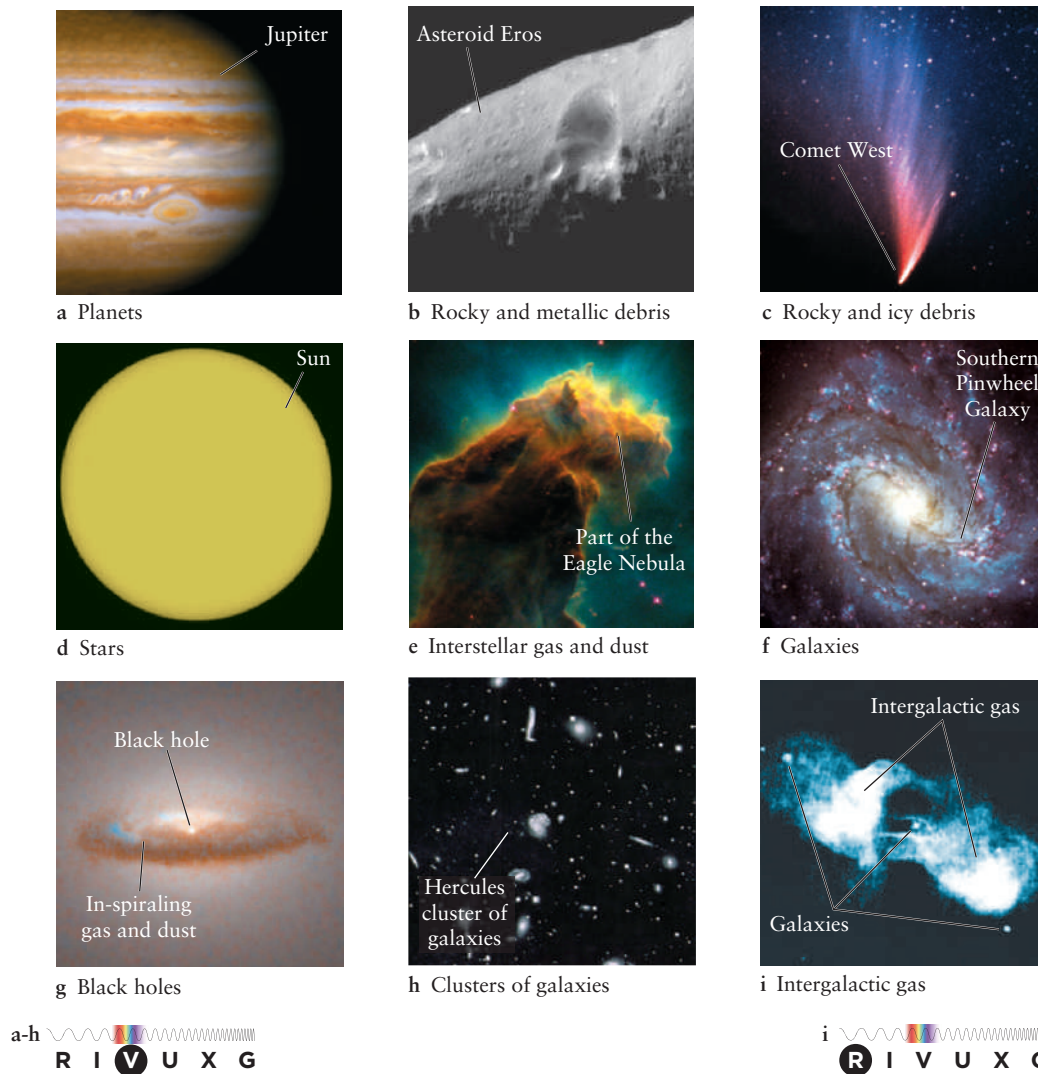


FIGURE 1-3 Inventory of the Universe Pictured here are examples of the major categories of objects that have been found throughout the universe. The black hole is in the center of the bright dot in (g). You will discover more about each type of object in the chapters that follow. (a: NASA/Hubblesite; b: NASA;

c: Peter Stattmayer/ESO; d: Big Bear Solar Observatory/New Jersey Institute of Technology; e: NASA/Jeff Hester & Paul Scowen; f: Australian Astronomical Observatory/David Malin Images; g: NASA; h: NOAO/AURA/NSF; i: Image courtesy of NRAO/AUI/NSF)

1-2 Well-known constellations make locating more obscure stars and constellations easy

1 People have known for millennia how to find the direction north in locations where the Big Dipper is visible. To do this, locate the Big Dipper (the asterism in the constellation Ursa Major) and imagine that its bowl is resting on a table (**Figure 1-5**). If you see the dipper upside down in the sky, as you frequently will, imagine the dipper resting on an upside-down table above it. Locate the two stars of the bowl farthest from the Big Dipper's handle. These are called the *pointer stars*. Draw a mental line through these stars in the direction away from the table, as shown in Figure 1-5. The first *moderately bright* star you then encounter is Polaris,

also called the *North Star* because it is located almost directly over Earth's North Pole. So, while Polaris is not even among the 20 brightest stars (see Appendix E-6), it is easy to locate. Whenever you face Polaris, you are facing north. East is then on your right, south is behind you, and west is on your left. (There is no equivalent star over the South Pole.)

The Big Dipper also illustrates the fact that being familiar with just a few constellations makes it easy to locate less distinctive stars and other constellations. The most effective way to do this is to use vivid visual connections, especially those of your own devising. For example, imagine gripping the handle of the Big Dipper and slamming its bowl straight down onto the head of Leo (the Lion). Leo comprises the first group of bright stars your bowl encounters. As shown in Figure 1-5, the brightest