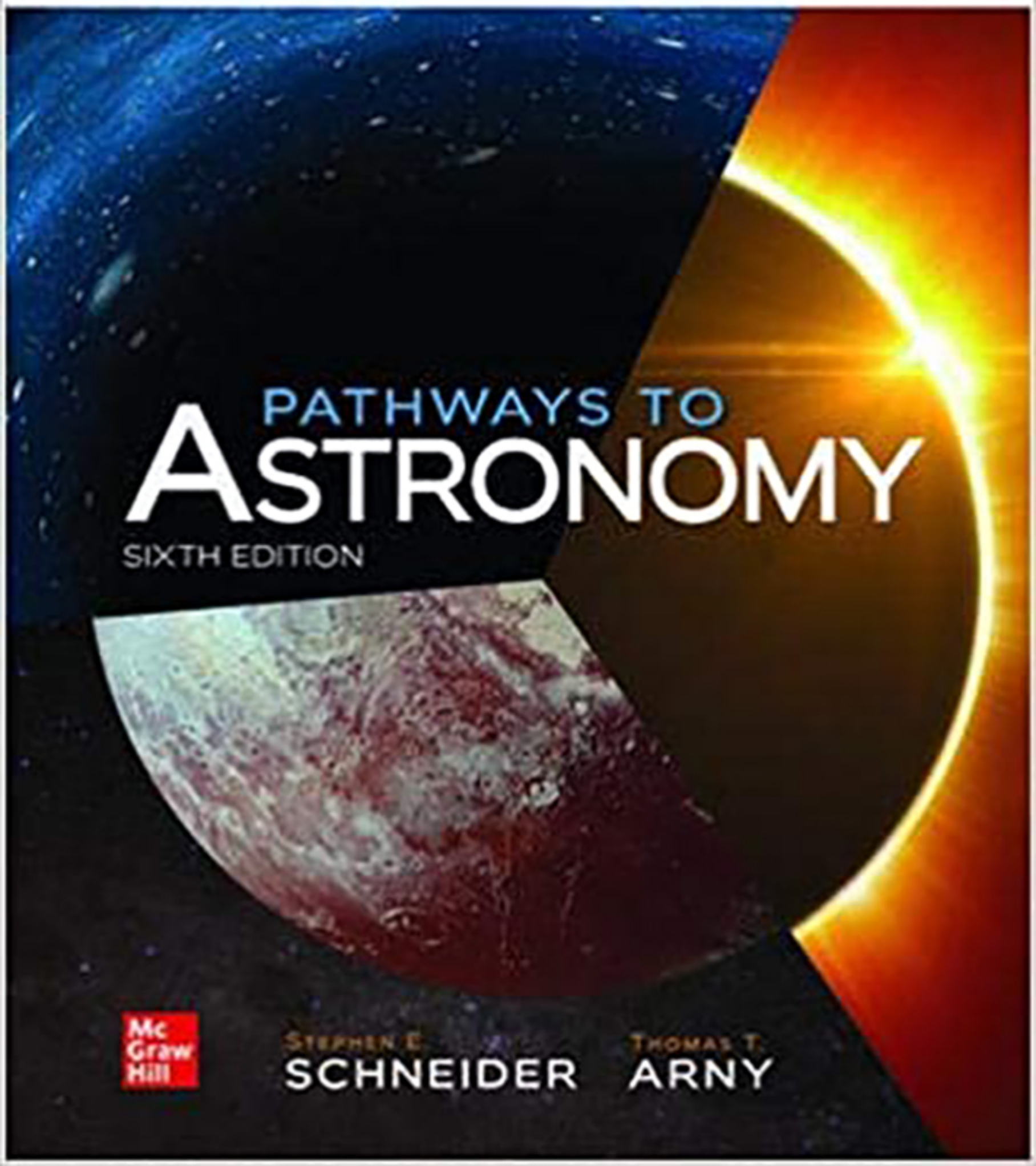
PATHWAYS TO
ASTRONOMY
SIXTH EDITION
Mc Graw Hill
STEPHEN E. SCHNEIDER
THOMAS T. ARNY

PATHWAYS TO ASTRONOMY

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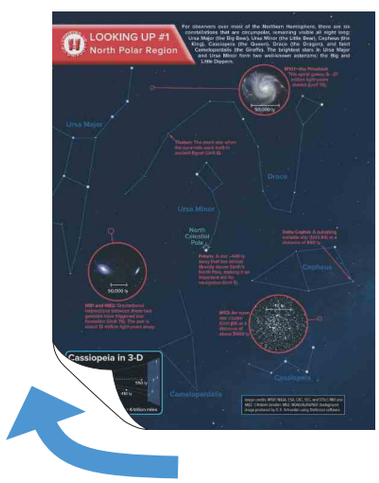


Looking Up at the night sky is one pathway to astronomy. The beauty of the night sky, the pattern of stars in their ancient constellations, invites us to wonder about our place in the universe. A small telescope shows even more remarkable sights, and further study reveals exotic and violent phenomena of terrible splendor. The nine "Looking Up" figures on the following pages dispaly a few of the amazing objects that fill the cosmos. Brief descriptions of each object list the Units where you can learn more about them.

LOOKING UP #1
North Polar Region

For observers over most of the Northern Hemisphere, there are six constellations that are circumpolar, remaining visible all night long: Ursa Major (the Big Bear), Ursa Minor (the Little Bear), Cepheus (the King), Cassiopeia (the Queen), Draco (the Dragon), and faint Camelopardalis (the Giraffe). The brightest stars in Ursa Major and Ursa Minor form two well-known asterisms: the Big and Little Dippers.

M101—the Pinwheel: This spiral galaxy is ~21 million light-years distant (Unit 75).

Ursa Major

Thuban: The north star when the pyramids were built in ancient Egypt (Unit 6).

Draco

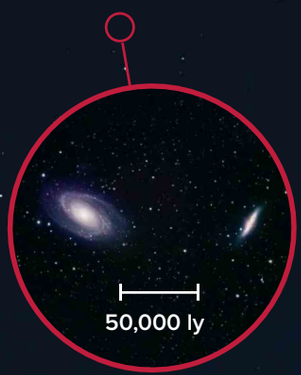
Ursa Minor

North Celestial Pole

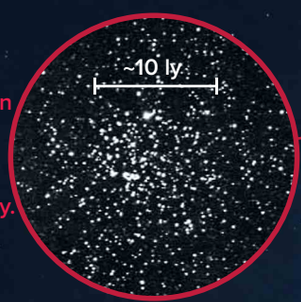
Polaris: A star ~440 ly away that lies almost directly above Earth's North Pole, making it an important aid for navigation (Unit 5).

Delta Cephei: A pulsating variable star (Unit 64) at a distance of 890 ly.

Cepheus

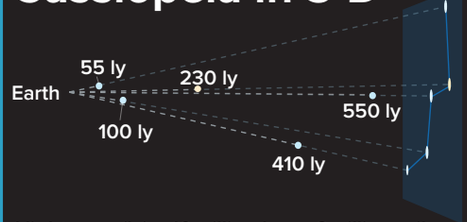


M81 and M82: Gravitational interactions between these two galaxies have triggered star formation (Unit 76). The pair is about 12 million light-years away.



M52: An open star cluster (Unit 69) at a distance of about 5000 ly.

Cassiopeia in 3-D



1 light-year (ly) = 10 trillion km = 6 trillion miles

Cassiopeia

Camelopardalis

Image credits: M101: Source: NASA, ESA, CXC, SSC, and STScI; M81 and M82: ©Robert Gendler; M52: Source: NOAO/AURA/NSF; Background image produced by S. E. Schneider using *Stellarium* software.

LOOKING UP #2
Ursa Major

Circling in the northern sky is the well-known Big Dipper, an ***asterism*** in the constellation Ursa Major. From midnorthern latitudes its seven stars are easy to see throughout the night. The Big Dipper can help you find Polaris, in the Little Dipper, and Arcturus, in Boötes. Ursa Major is home to several other intriguing objects that you can find with a small telescope on a dark, clear night.

Polaris

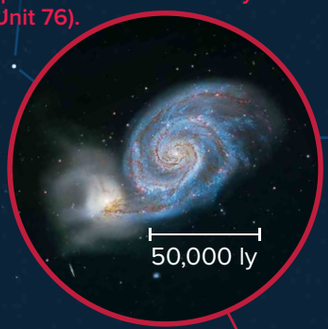
Draco

Little Dipper

Ursa Minor

Over the course of a night, stars appear to rotate counterclockwise around the star Polaris, which remains nearly stationary because it lies almost directly above Earth's North Pole. Polaris is not especially bright, but you can easily find Polaris by extending a line from the two stars at the end of the bowl of the Big Dipper, the pointer stars, as shown by the dashed line (Unit 13).

M51—The Whirlpool Galaxy: This interacting galaxy looks like a dim patch of light with a small telescope. M51 is ~28 million ly away (Unit 76).

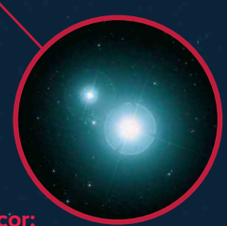


Location of the Hubble Deep Field (Unit 76)

Pointer stars

Ursa Major

Big Dipper



M97—The Owl: This planetary nebula (Unit 65) is ~2500 ly away.

Boötes

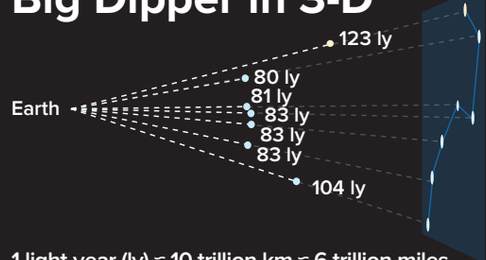
Follow the arc of the Big Dipper's handle to Arcturus

Mizar and Alcor: If you look closely, you may notice that the middle star in the Big Dipper's handle is actually two stars. Despite appearing close together in the sky, they are probably not in orbit around each other. However, with a small telescope, you can see that Mizar (the brighter of the two stars) has a faint companion that orbits it. Moreover, each of Mizar's stars is itself a binary star, making Mizar a quadruple system (Unit 57).

Leo Minor

Arcturus: A red giant (Unit 63) that is 37 light-years distant.

Big Dipper in 3-D



1 light-year (ly) = 10 trillion km = 6 trillion miles

Image credits: M51: ©Tony and Daphne Hallas; Mizar and Alcor: Source: Courtesy of DSS/Processing by Coelum (www.coelum.com); M97: Source: Gary White and Verlenne Monroe/Adam Block/NOAO/AURA/NSF; Background image produced by S. E. Schneider using *Stellarium* software.

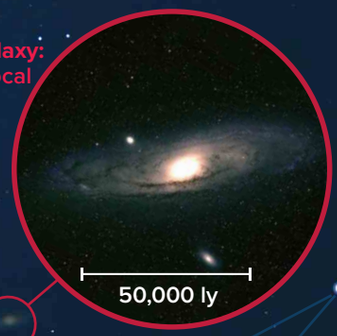
LOOKING UP #3
Andromeda & Perseus

In this region, you can find the first and third most luminous galaxies in our Local Group (the Milky Way is second). Both galaxies are about 2.5 million light-years from us—the most distant objects visible with the naked eye. Northern Hemisphere viewers can view this region in the evening sky from August through December.

Pegasus

Cassiopeia

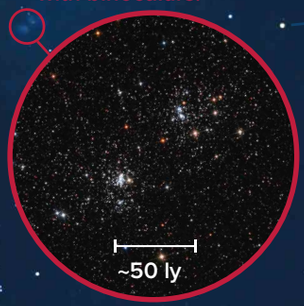
M31 — The Andromeda Galaxy: The largest galaxy in the Local Group is easy to see with binoculars (Unit 77).



The Great Square

Three bright stars in Pegasus together with the "head" of Andromeda make up an easy-to-spot asterism known as the Great Square.

The Double Cluster: This pair of open clusters (Unit 70) is about 7500 ly away and easy to spot with binoculars.



Andromeda

M33 — The Triangulum Galaxy: Just slightly more distant than M31, but much more challenging to see. Look for it with averted vision (Unit 33) from a very dark sky.

Triangulum

Pisces

Perseus

Algol: The "demon star," dims for about 10 hours every few days as its companion eclipses it (Unit 58).

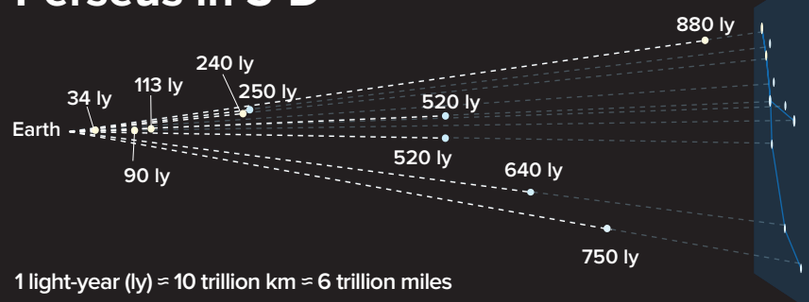
Aries

California Nebula: An emission nebula (Unit 73) shaped like the state of California. You may be able to capture its faint red glow with a long exposure photograph (Unit 33).

Cetus

Mira: A highly variable red giant (Unit 65) that is usually too dim to see, but for a month or two out of every 11, it becomes one of the brightest stars in Cetus.

Perseus in 3-D



1 light-year (ly) ≈ 10 trillion km ≈ 6 trillion miles

Image credits: M31: Courtesy of George Greaney; The Double Cluster: ©Neil Fleming; Background image produced by S. E. Schneider using *Stellarium* software.

LOOKING UP #4
The Summer Triangle

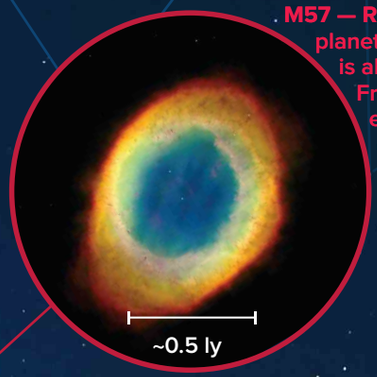
The Summer Triangle is an asterism of the three brightest stars in the constellations Cygnus (the swan), Lyra (the lyre), and Aquila (the eagle). They rise in the east shortly after sunset in late June and are visible throughout the northern summer and into late October (when they set in the west in the early evening). Vega looks the brightest to us, but Deneb produces the most light, only looking dimmer because it is so much more distant.

Cygnus X-1: This dim star, visible with binoculars, is orbited by a 15 solar mass black hole (Unit 69).

Epsilon Lyrae: A double, double star

Vega

M57 — Ring Nebula: This planetary nebula (Unit 65) is about 2300 ly distant. From its observed expansion rate, it is estimated to be 7000 years old.



Lyra

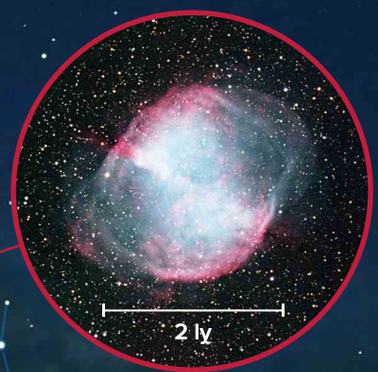
Deneb

Deneb is a blue supergiant (Unit 67), one of the most luminous stars we can see. Deneb emits ~50,000 times more light than the Sun.

Summer Triangle

Cygnus

Vulpecula



M27 — Dumbbell Nebula: Another planetary nebula (Unit 65), the Dumbbell is about 1300 ly distant and is about 2.5 ly in diameter.

Sagitta

Albireo: Through a small telescope, this star pair shows a strong color contrast between the orange red giant and blue main-sequence star (Unit 59). These stars may orbit each other every few hundred thousand years, but they are far enough apart that they may not be in orbit.

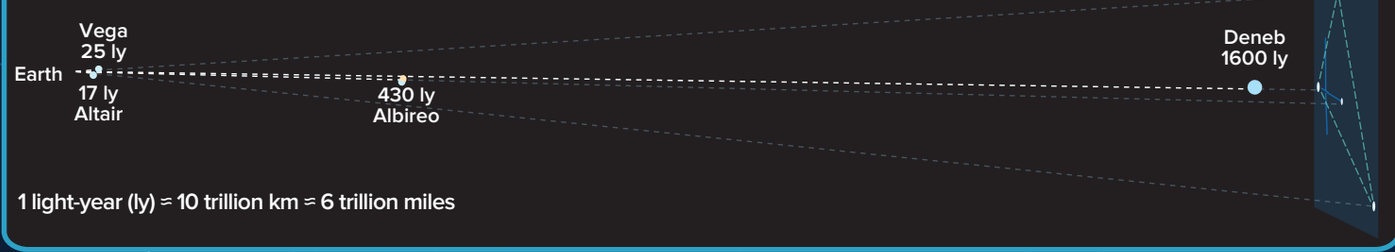
Altair

Aquila

Delphinus

Image credits: M57: Source: The Hubble Heritage Team (AURA/STScI/NASA); M27: Source: ESO/I. Appenzeller, W. Seifert, O. Stahl; Albireo: Source: Courtesy of Randy Brewer; Background image produced by S. E. Schneider using *Stellarium* software.

The Summer Triangle in 3-D



1 light-year (ly) ≈ 10 trillion km ≈ 6 trillion miles

LOOKING UP #5
Taurus

Taurus, the Bull, is one of the constellations of the zodiac and one of the creatures hunted by Orion in mythology. Taurus is visible in the evening sky from November through March. The brightest star in Taurus is Aldebaran, the eye of the bull. The nebula and two star clusters highlighted here have been critical in the history of astronomy for understanding the distances and fates of stars.

Pollux

Castor: A 6-star system consisting of three spectroscopic binaries in orbit about each other (Unit 57). Most of the light comes from a B-type main-sequence star.

Capella: What looks like a single bright star is actually a spectroscopic binary (Unit 57) of two giants orbiting closer to each other than Earth from the Sun.

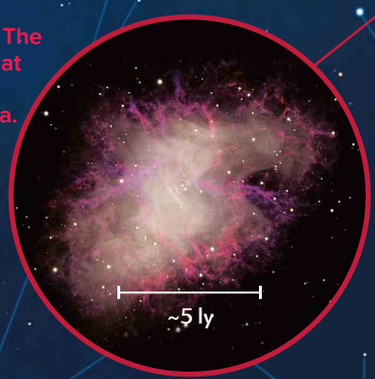
Gemini

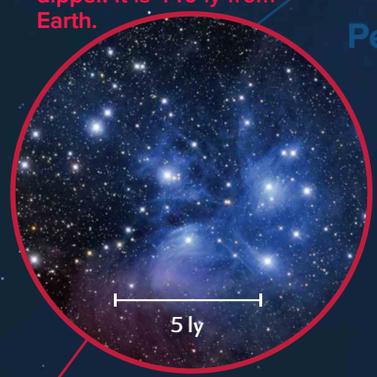
Auriga

M45 — Pleiades: An open star cluster (Unit 70) that is easy to see with the naked eye and looks like a tiny dipper. It is 440 ly from Earth.

Perseus

M1 — Crab Nebula: The remnant of a star that blew up in the year 1054 as a supernova. At its center is a pulsar (Unit 68). It is ~6500 ly distant.





Taurus

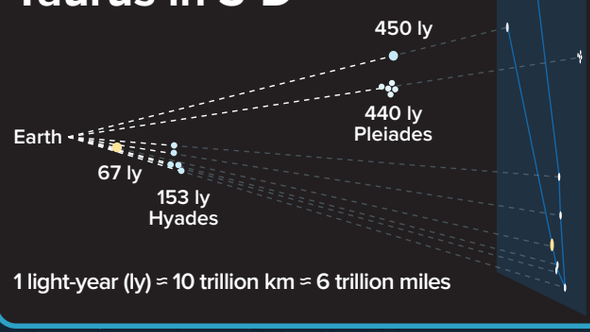
Orion

Aldebaran: A red giant star (Unit 63). It is 65 ly from Earth and has a diameter ~45 times larger than the Sun's. Although it lies in the direction of the Hyades, it is less than half as distant.

Hyades: The "V" in Taurus is a nearby star cluster, measured to be 153 ly away by the Gaia satellite (Unit 54). It is easy to see its many stars with binoculars.

Aries

Taurus in 3-D



1 light-year (ly) ≈ 10 trillion km ≈ 6 trillion miles

T Tauri: An erratically varying pre-main-sequence star, prototype of a class of forming stars (Unit 61). It is about 470 ly distant.

Image credits: M1: ©Courtesy of Richard Wainscoat; M45: Stocktrek Images/Getty Images; Background image produced by S. E. Schneider using *Stellarium* software.

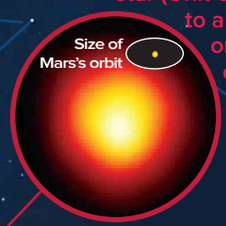
LOOKING UP #6
The Winter Triangle

The Winter Triangle is an asterism of bright stars in the constellations of Orion the hunter and his two dogs, Canis Major and Canis Minor. Orion's distinctive belt of three bright stars lies almost on the celestial equator, so it is visible from both hemispheres. The region contains many of the brightest stars and one of easiest nebulae to see through a telescope. Evening viewing is best fom November to April, and before dawn from August through September.

Procyon: Like Sirius, this third corner of the "Winter Triangle" asterism has a white dwarf obiting it, but it is exceptionally difficult to see, even through a telescope .

Canis Minor

Betelgeuse: A red supergiant star (Unit 63) that has swelled to a size larger than the orbit of Mars. Its red color indicates that it is relatively cool for a star, about 3500 K.



Taurus

Monoceros

Orion

Winter Triangle

Horsehead Nebula: The horsehead shape is produced by dust in an interstellar cloud blocking background light (Unit 73).

Celestial Equator

Sirius: The brightest star in the night sky, 8.6 ly distant. It is orbited by a white dwarf (Unit 65) visible with a telescope.

Rigel: A blue supergiant star (Unit 67). Its blue color indicates a surface temperature of about 10,000 K.

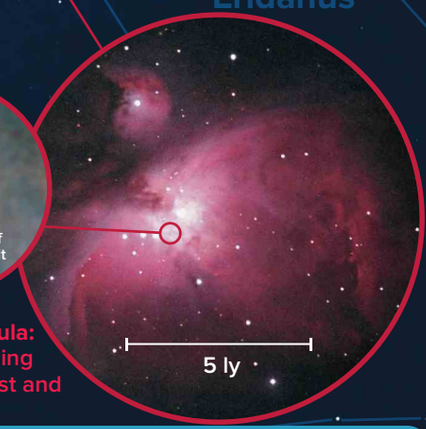
Lepus

Eridanus

Canis Major

Adhara: Based on its space velocity (Unit 54), astronomers estimate this star was 10 times brighter than Sirius, rivalling Venus, 4.7 million years ago.

Protoplanetary disk: Our Solar System may have looked like this when it formed (Unit 36).



M42 — Orion Nebula: An active star-forming region rich with dust and gas (Units 61, 73).

Puppis

Orion in 3-D

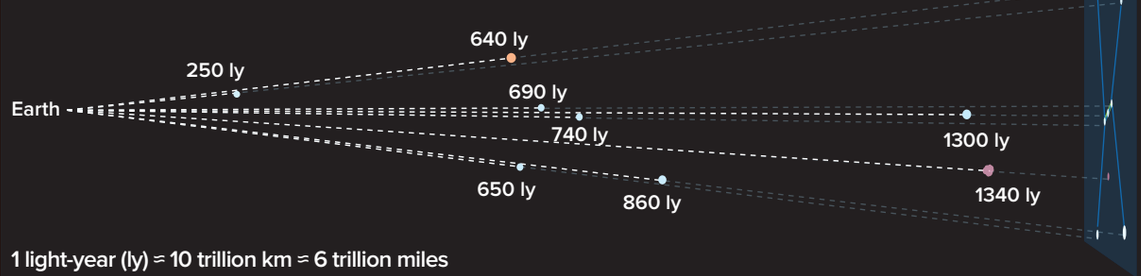
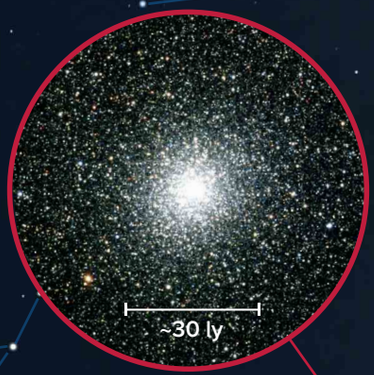


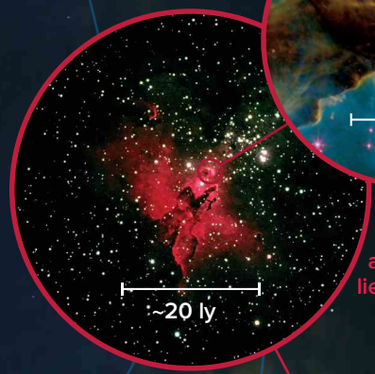
Image credits: Betelgeuse: Source: Andrea Dupree (Harvard-Smithsonian CfA), Ronald Gilliland (STScI), NASA and ESA; Horsehead Nebula: Source: NOAO/AURA/NSF; M42: ©Carol B. Ivers and Gary Oleski; Proplyds: Source: C.R. O'Dell/Rice University; NASA; Background image produced by S. E. Schneider using *Stellarium* software.

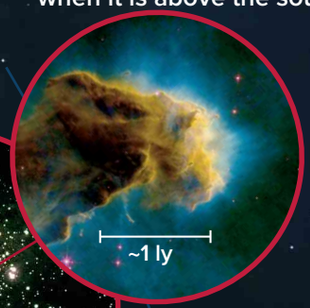
LOOKING UP #7
Sagittarius

Sagittarius marks the direction to the center of the Milky Way. It can be identified by the "teapot" shape of its brighter stars, with the Milky Way seeming to rise like steam from the spout. Many star-forming nebulae and globular clusters are found here, and the Sun, Moon, and planets may be seen in their travels near the ecliptic. From northern latitudes, the region is best viewed July to September, when it is above the southern horizon in the evening.



M22: A globular cluster (Unit 70) just barely visible to the naked eye. It is ~10,100 ly distant from us.





M16 — Eagle Nebula: This young star cluster and the hot gas around it lie about 5700 ly from Earth.

Barnard's Star: The next nearest star after the Alpha Centauri system is visible through a small telescope. It has the largest proper motion (Unit 54) of any star—more than 10 arc seconds per year.

Ophiuchus
Sometimes called the 13th sign of the zodiac because the Sun crosses through Ophiuchus at the beginning of December.

M8 — Lagoon Nebula

Sagittarius

Ecliptic

The "teapot" of Sagittarius

Center of the Milky Way (Unit 74)

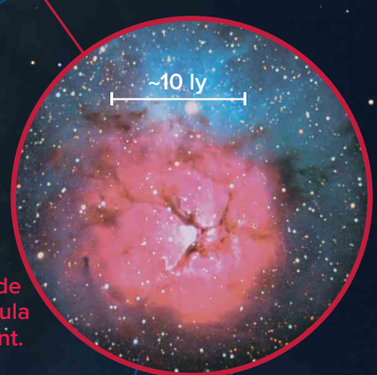
Antares: A red supergiant (Unit 59) whose name means "rival to Mars" (Ares in Greek).

Corona Australis

Scorpius

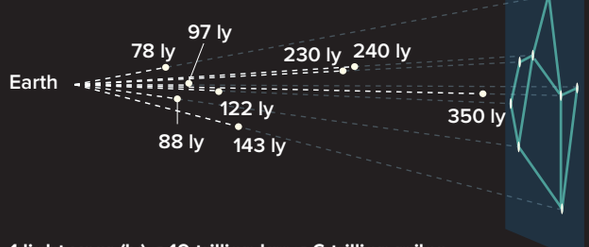
Libra

Telescopium



M20 — Trifid Nebula: The name Trifid was given because of the dark streaks that divide it into thirds. The nebula is about 4100 ly distant.

The Teapot in 3-D



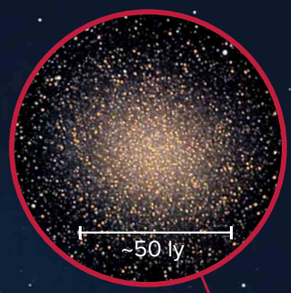
1 light-year (ly) ≈ 10 trillion km ≈ 6 trillion miles

Image credits: M22: Courtesy of N.A. Sharp, REU program/NOAO/AURA/NSF; M16: Courtesy of Bill Schoening/NOAO/AURA/NSF; M16 close-up: Source: NASA, ESA, STScI, J. Hester and P. Scowen (Arizona State University); M20: ©Jason Ware/Galaxy Photography; Background image produced by S. E. Schneider using *Stellarium* software.

This region contains many intriguing objects—the nearest star and one of the most massive known. They are best observed from the Southern Hemisphere. Northern-Hemisphere viewers can see Centaurus low in the southern sky during evenings in May–July, but Crux, the Southern Cross, rises above the horizon only for viewers south of latitude 25°N (Key West, South Texas, and Hawaii in the United States).

LOOKING UP #8
Centaurus and Crux

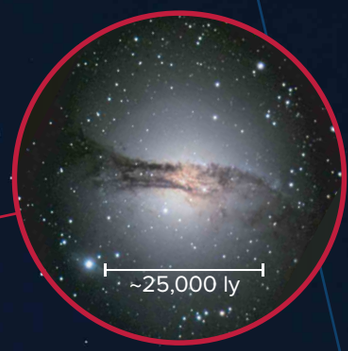
Scorpius



Omega Centauri: The largest globular cluster (Unit 70) in the Milky Way, ~16,000 ly distant and containing millions of stars.

Norma

Lupus



Centaurus A: This active galaxy (Unit 78), ~13 million ly distant, is one of the brightest radio sources in the sky.

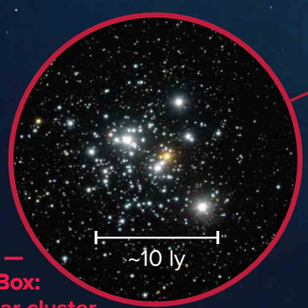
Centaurus

Alpha Centauri

Proxima Centauri: This dim star is the nearest star to the Sun, 4.24 ly distant (Unit 54). It takes about half a million years to orbit Alpha Centauri, which is itself a binary star.

Circinus

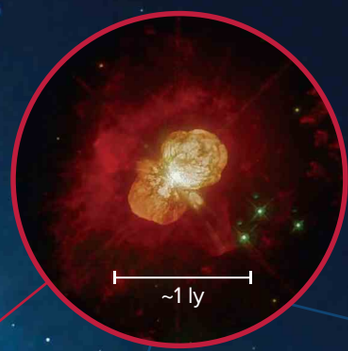
Crux



NGC 4755 — the Jewel Box: An open star cluster (Unit 70) ~7500 ly from us.

Musca

The Coal Sack: An interstellar dust cloud (Unit 73).



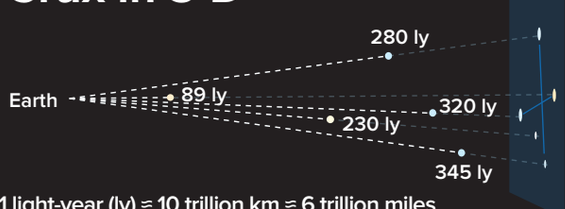
Eta Carinae: At over 100 times the mass of the Sun, this is one of the highest-mass stars known and doomed to die young (Unit 61). It is about 8000 ly distant.

Carina

Octans

Vela

Crux in 3-D



1 light-year (ly) ≈ 10 trillion km ≈ 6 trillion miles

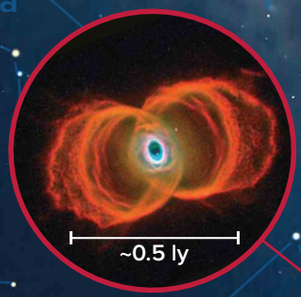
Image credits: Omega Centauri: ©Al Kelly/KellySky.net; Centaurus A: Source: ESO; NGC 4755: Source: Research School of Astronomy and Astrophysics, The Australian National University; Eta Carinae: Source: NASA, J. Hester (Arizona State University); Background image produced by S. E. Schneider using *Stellarium* software.

LOOKING UP #9
South Polar Region

The south celestial pole lies in the constellation Octans, named after a navigational instrument. The stars in this region are dim, but the bright stars of Crux (the Southern Cross) point approximately toward the pole. Observers in much of the Southern Hemisphere can see the Magellanic Clouds—two small galaxies that orbit the Milky Way—circling the south celestial pole throughout the night.

Ara

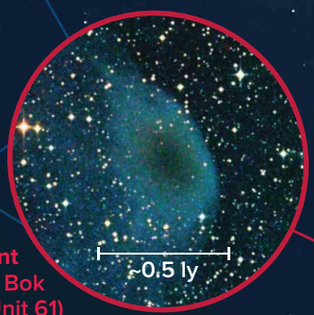
Hourglass Nebula: A planetary nebula (Unit 65) ~8000 ly distant.



Circinus

Triangulum Australis

Pavo



Thumbprint Nebula: A Bok globule (Unit 61) about 600 ly distant.

Apus

Crux, the Southern Cross

Toward south celestial pole

Musca

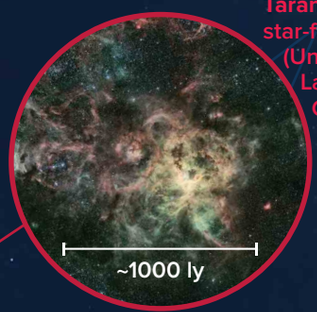
Octans

South Celestial Pole

Chamaeleon

Small Magellanic Cloud: A dwarf galaxy orbiting the Milky Way at a distance of ~200,000 ly (Unit 77).

Tarantula Nebula: A star-formation region (Unit 60) in the Large Magellanic Cloud larger than any known in the Milky Way.



Mensa

Tucana

Hydrus

Large Magellanic Cloud: A small galaxy orbiting the Milky Way at a distance of ~160,000 ly (Unit 77).

Carina

Reticulum

Pictor

Canopus: The second-brightest star in the night sky, 310 ly from Earth. It has completed its main sequence phase and is currently fusing helium in its core (Unit 63).

Dorado

Image credits: Hourglass Nebula: Source: Raghvendra Sahai and John Trauger (JPL), the WFPC2 Science Team, and NASA; Thumbprint Nebula: S. E. Schneider; Tarantula Nebula: Source: ESO/R. Fosbury (ST-ECF); Background image produced by S. E. Schneider using *Stellarium* software.

PATHWAYS TO ASTRONOMY

SIXTH EDITION

Stephen E. Schneider
Professor of Astronomy
University of Massachusetts, Amherst

Thomas T. Arny
Professor of Astronomy, Emeritus
University of Massachusetts, Amherst

Mc Graw Hill

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To my father, who taught me the night sky when I was little.

—Steve

About the Authors

Stephen E. Schneider is a professor and Thomas T. Arny is an emeritus professor in the Astronomy Department at the University of Massachusetts at Amherst, which is part of the Five College Astronomy Department (comprising faculty from UMass and Amherst, Hampshire, Mt. Holyoke, and Smith Colleges). Both are recipients of their college's Outstanding Teacher Award, and they have collectively taught introductory astronomy for over 50 years to students with a wide variety of backgrounds.

Steve Schneider became interested in astronomy at the amateur level when he was a child. He studied astronomy as an undergraduate at Harvard and obtained his Ph.D. from Cornell. His dissertation work received the Trumpler Award of the Astronomical Society of the Pacific, and he was named a Presidential Young Investigator. In addition to teaching introductory astronomy, he works closely with science teachers, presenting workshops and special courses. He also loves to draw and paint.

Tom Arny received his undergraduate degree from Haverford College and his Ph.D. in astronomy from the University of Arizona. In addition to his interest in astronomy, he has a long-standing fascination with the natural world: weather (especially atmospheric optics such as rainbows), birds, wildflowers, and butterflies.

Brief Contents

Contents

PART 2 PROBING MATTER, LIGHT, AND THEIR INTERACTIONS

PART 3 THE SOLAR SYSTEM

PART 4 STARS AND STELLAR EVOLUTION

PART 5 GALAXIES AND THE UNIVERSE

Preface

APPROACH

There are many astronomy textbooks available today, but *Pathways to Astronomy* offers something different.

Created by two veteran teachers of astronomy, both recipients of outstanding teaching awards, *Pathways* breaks down introductory astronomy into its component parts. The huge and fascinating field of astronomy is divided into 86 Units from which you can selectively choose topics according to your interests, while maintaining a natural flow of presentation.

One of the frustrations created by other current astronomy textbooks is that each chapter covers such a wide array of topics that it is difficult to absorb the large amount of material. Further, the texts are wed to such a specific order of presentation that it is difficult for the instructor to link the chapter readings and review questions to his or her own particular approach to teaching the subject. Whether you are learning astronomy for the first time or teaching it for the tenth, *Pathways* offers greater flexibility for exploring astronomy in the way you want.

The Unit structure allows the new learner and the veteran professor to relate the text more clearly to college lectures. Each Unit is small enough to be easily tackled on its own or read as an adjunct to the classroom lecture. For the instructor who is designing a course to relate to current events in astronomy or a particular theme, the structure of *Pathways* makes it easier to assign reading and worked problems that are relevant to each topic. For the student of astronomy, *Pathways* makes it easier to digest each topic and to return to specific topics for review.

Each Unit of *Pathways* focuses on a single topic or closely related set of ideas. The same material covered in other introductory astronomy texts is included, but it is broken up into smaller, self-contained parts. And because the questions and problems are based on specific ideas, there are fewer gaps in what the questions cover, and it is easier to determine mastery. This approach allows greater flexibility in selecting topics than is possible with the wide-ranging chapter in a traditional text that covers the same material as three or more *Pathways* Units.

The Units are written to flow naturally from one to the next when following their traditional order of presentation. However, they are also written to be read independently in alternative orders—different *pathways*—through the book. Instructors can select Units to fit their course needs and cover them in the order they prefer. For example, when presenting a specific topic in planetary, stellar, or galactic astronomy, we find it useful to assign individual Units that cover the related physics of gravity or light in conjunction with them. In a course focusing on stars and galaxies, some of the results from studies of exoplanetary systems might be added to a lecture on interstellar clouds and star formation. In a course focusing on the Solar System, Units that present an overview of stellar evolution

and cosmology provide an opportunity for placing our local piece of the universe in a broader context. It is especially easy to tailor the order of readings when putting together a course using the book in an electronic format, where the readings and ancillary material can be assigned through McGraw-Hill's website.

The Unit format also provides an opportunity to take some extra steps beyond the ordinary text. The authors have included some material of special interest that most introductory texts do not offer—for example, Units on calendar systems and special relativity. Units like these might be assigned for independent reading to complement other material in lecture. More advanced material within a particular Unit topic is also organized toward the end of the Unit so that the essentials are covered first—also providing flexibility for assigning readings.

Pathways to Astronomy makes it easy to tailor readings and exercises so they fit best within a course's structure. It also provides opportunities to travel down some fascinating paths to enhance a course or to provide additional reading for advanced students.

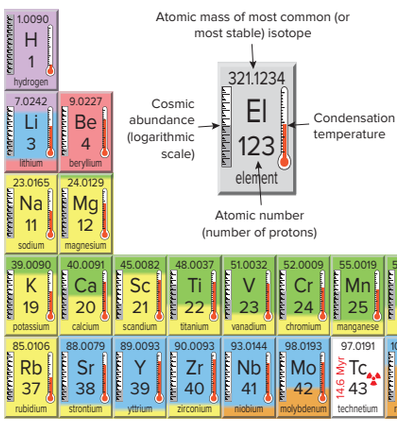
NEW TO THE SIXTH EDITION

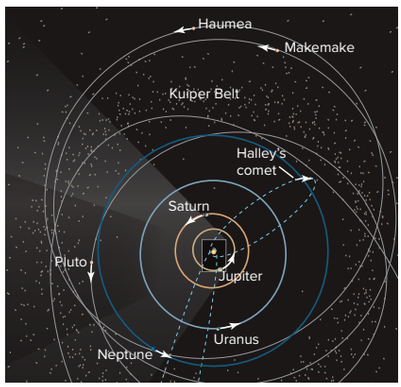
For every new edition, we scan the literature and popular press to include the most interesting recent results. The excellent suggestions of readers and reviewers are also much appreciated for updates and improvements to *Pathways*. One of the more challenging aspects of revising the text is that we want to address new topics and offer clarifications of complex issues, but at the same time we want to resist the temptation to expand the text unnecessarily. Most of the additions can simply replace older material, but some results, such as the rapidly expanding data on exoplanets, required some expansion of the text.

The Unit topics remain the same as for the past three editions, with the most significant updates to individual Units noted here. We also made a few broad changes that extend beyond individual Units:

1. The recent detection of a neutron-star merger and its aftermath has confirmed hypotheses about the production of many of the heavy elements in the periodic table, providing a clear story to tell about the origin of the elements. We now present a more detailed explanation of these origins throughout the book, both in individual Units where the astronomical events are discussed and in the Cosmic Periodic Table that accompanies the book.
2. Another set of changes represents our effort to help readers relate the astronomy of the text to what they see on the sky. We have created a number of figures of the sky (including the background images in the Looking Up pieces) using the free open-source program *Stellarium,* and we have added a number of projects based on this excellent software that are noted in the margins where they connect to a subject under discussion. We hope these changes will give readers the incentive and pathway for better appreciating what they read.
3. To bring in recent news, anticipated space missions, and current research topics, we have added a new feature called "Cosmic Frontiers." These entries appear in marginal boxes, giving us a place to talk about exciting new material that perhaps will be included as part of the regular text in the future.

In all, more than 80 figures were added, updated, or replaced throughout the book to improve clarity and to include some of the best new images available. We also continue to use information gleaned from LearnSmart, McGraw-Hill's adaptive learning program, to aid in the revisions. LearnSmart links readers' responses to questions about the content to the sections of the text where the question's subject matter is discussed. We focused our efforts at clarifying wording on material that students found most challenging.





Details of Changes The following list of changes includes the most significant updates and additions:

Unit 1 Our Planetary Neighborhood: Orbits of Haumea and Makemake added to figure. Updates on *Voyager 1* and *2*.

Unit 4 Scientific Foundations of Astronomy: New version of the cosmic periodic table introduced that provides more detailed estimates of the origins of the elements based on recent research.

Unit 5 The Night Sky: Constellation artwork from antique star charts added.

Unit 10 Geometry of the Earth, Moon, and Sun: Added *Clarification Point* about the current "flat-Earth" conspiracy fad and a *Stellarium* project to understand the effects of Earth being round on observations.

Unit 11 Planets: The Wandering Stars: New illustration of retrograde motion. Replaced pictures of astronomers with more contemporaneous portraits.

Unit 18 Orbital and Escape Velocities: Added note about Oumuamua's hyperbolic trajectory and speculation about its source.

Unit 22 The Electromagnetic Spectrum: New illustration of Newton's *Opticks* experiment to converge a spectrum back into white light.

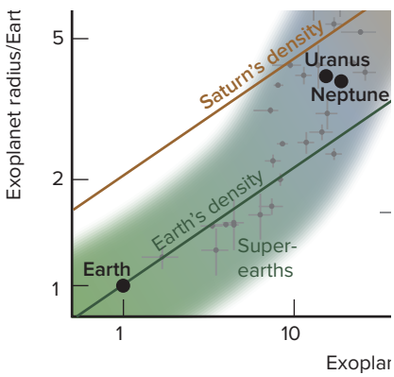
Unit 25 The Doppler Shift: Updated figure to better illustrate Doppler shifts of both sound and light.

Unit 27 General Relativity: New illustration of system of GPS satellites.

Unit 29 Collecting Light: New rendering of the ELT.

Unit 31 Telescope Resolution: New image of wave diffraction, and a new illustration showing how the VLT operates as an interferometer.

Unit 35 The Origin of the Solar System: Updated discussion of Solar System formation in the context of star formation.



Unit 36 Other Planetary Systems: New ALMA image of protoplanetary disk. Expanded and revised coverage of exoplanets; new diagram illustrating selection effects of detection methods; updated figures showing layout of multiple-exoplanet systems and exoplanet densities. Updated key terms from proper motion and gravitational lensing methods to astrometric and microlensing methods to reflect most common usage.

Unit 37 Earth as a Terrestrial Planet: Update to topographic map of Earth to improve clarity.

Unit 40 Mercury: Substantial updating of text along with several new and updated images from *Messenger,* including improved image of troughs and contrasted-color images of vents, hollows, and Caloris. Discussion of current hypothesis about origin of Mercury's strong magnetic field, and revised discussion and figure explaining Mercury's 3:2 resonance.

Unit 41 Venus: Replaced discussion of cause of Venus's retrograde rotation based on recent modeling that suggests resonance plays a bigger role than previously thought.

Unit 42 Mars: New *Curiosity* and *Opportunity* images and comparison image of the different rovers. New images of polar caps, shown to scale and showing seasonal change in size. Updated discussion of seasonal changes and changes in axis tilt due to gravitational perturbations by Jupiter.

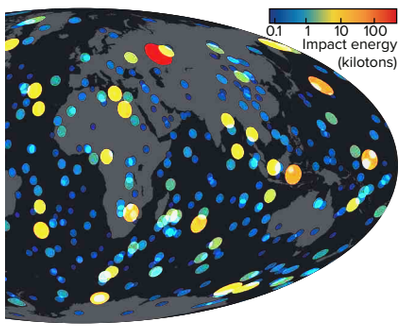
Unit 43 Asteroids: New image and discussion of early results from asteroid sample-return missions by JAXA and NASA.

Unit 44 Comparative Planetology: Added discussion comparing Solar System planets to exoplanet results.

Unit 45 Jupiter and Saturn: Gas Giants: Discussion of recent *Juno* results and image of Jupiter's polar region; new rendering of Saturn without rings.

Unit 46 Uranus and Neptune: Ice Giants: New discussion and illustration of differences between interiors of Uranus and Neptune based on recent modeling.

Unit 47 Satellite Systems and Rings: New image of Iapetus better illustrating its contrasting hemispheres. Improved illustration of Roche limit.



Unit 48 Ice Worlds, Pluto, and Beyond: Image and early results from Ultima Thule flyby.

Unit 49 Comets: New images of Comet Churyumov-Gerasimenko. Added art and discussion of Oumuamua.

Unit 50 Impacts on Earth: Improved image of meteor. Distinction between meteoroid and asteroid as recommended by IAU noted and revised in text. New figure and discussion of bolides seen hitting Earth.

Unit 51 The Sun, Our Star: New image of spicules from the *Hinode* satellite. Updated illustraton of *Voyagers 1* and *2* and their entry into interstellar space.

Unit 52 The Sun's Source of Power: Added *Mathematical Insight* box to emphasize small fraction of Sun's mass lost to fusion.

Unit 53 Solar Activity: Improved illustration of Sun's differential rotation.

Unit 54 Surveying the Stars: Discussion of early findings from *Gaia* satellite, including close passages of stars to Solar System. New *Mathematical Insight* box about sexigesimal system. Improved illustration of aberration of starlight.

Unit 59 The H-R Diagram: To better link the idea of the H-R diagram to observational astronomy, all the identified stars in the diagram are now taken from stars visible in the Looking Up pieces.

Unit 60 Overview of Stellar Evolution: New schematic of cycling of material between stars and interstellar gas, noting important role of interactions of stellar remnants in producing some of the heavy elements.

Unit 61 Star Formation: Updated discussion about the most massive stars known.

Unit 64 Variable Stars: New illustration of Mira.

Unit 65 Mass Loss and Death of Low-Mass Stars: Updated text to describe how these stars contribute significantly to the production of some heavy elements.

Unit 66 Exploding White Dwarfs: Added more specific discussion of elements produced by Type Ia supernovae.

Unit 67 Old Age and Death of Massive Stars: Noted specific elements associated with core-collapse supernovae.

Unit 68 Neutron Stars: Reorganized material to emphasize processes taking place in binary systems in Section 68.3, which is retitled. Expanded discussion of magnetars and emphasized differences between emission powered by rotation and thermal emission from surface. New material added about neutron-star mergers, kilonovae, and production of the heaviest elements.

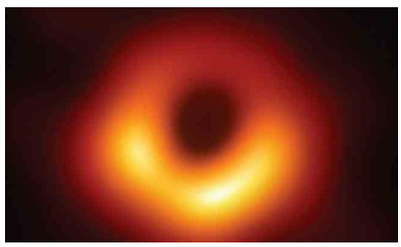
Unit 69 Black Holes: Added discussion of range of black hole masses detected by LIGO.

Unit 70 Star Clusters: Revised discussion of stellar associations and included the Ursa Major group under this classification.

Unit 74 Mass and Motions in the Milky Way: Updated image of stars orbiting Sgr A*, and mention the X-ray "chimney" feeding the gamma-ray bubbles around the center of the Galaxy.

Unit 76 Types of Galaxies: Clarified figure illustrating evolution through mergers.

Unit 77 Galaxy Clustering: Noted debated status of Canis Major dwarf galaxy.



Event Horizon Telescope Collaboration

Unit 78 Active Galactic Nuclei: Added first image of M87's supermassive black hole. Expanded discussion of interaction between supermassive black holes and the evolution of galaxies through the process of feedback. Section titles changed to reflect new content.

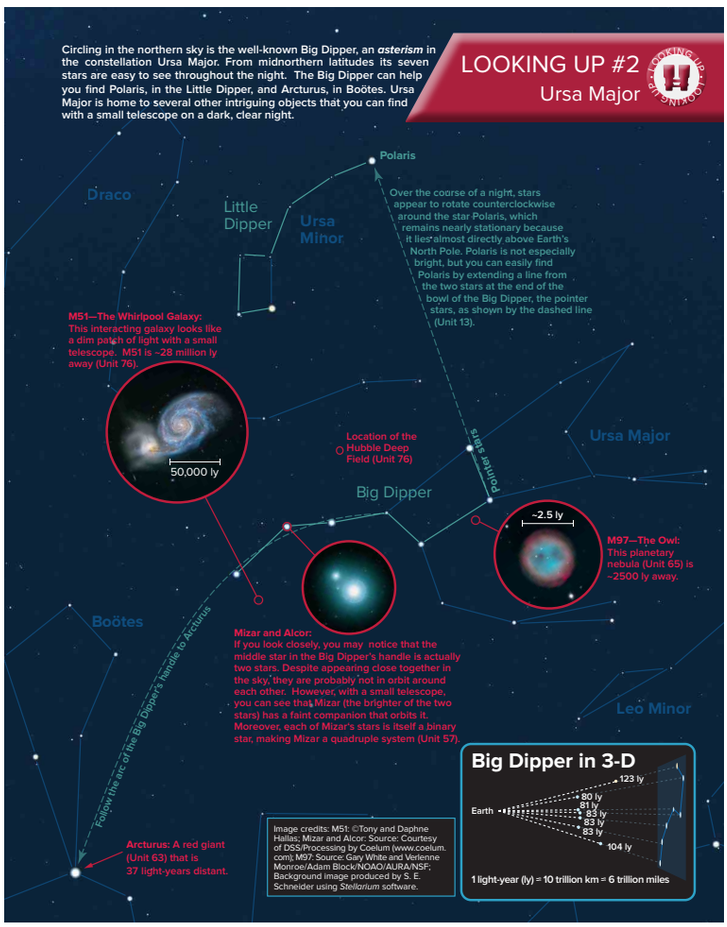
Unit 81 The Edges of the Universe: Improved illustration of cosmic horizon for different observers.

Unit 86 The Search for Life Elsewhere: Added some discussion of current status of SETI projects.

Appendix: Data in the tables have been updated with recent measurements. This applies particularly to data for some of the outer dwarf planets and their satellites, nearby stars, and some of the dwarf galaxies in the Local Group.

FEATURES OF THIS BOOK

Book Elements We suggest familiarizing yourself with some of the extra features of the book before reading individual Units. We have provided a variety of features that can help comprehend the wide-ranging material of this book:



Looking Up Illustrations: It can be challenging to link introductory astronomy to the sky around us. The nine "Looking Up" full-page art pieces at the beginning of the book provide another pathway to astronomy, connecting what we actually see when "looking up" at the night sky with the more theoretical side of astronomy. Each illustration has been created using *Stellarium* and covers an equal area of the sky that contains interesting constellations and features. Close-up images show some of the intriguing objects with cross-references to the text. We also provide three-dimensional illustrations of the constellations or other objects within the field of view.

Consistent Map Projections: There are myriad ways of presenting data from a spherical surface in a flat diagram, and there is very little consistency in what is published. We have gone back to the original source material to produce high-quality maps of planets and the sky using a single consistent Mollweide equal-area projection format that makes comprehension and comparison easier.

Tables of Useful Data and Formulas: The appendix includes a brief discussion of basic mathematical techniques along with many tables of essential astronomical data. Highlights include a table of useful astronomical formulas; data on planets, stars, and galaxies; and the Messier catalog.

Glossary: Following the appendix is a full glossary of all key terms used throughout the text. The glossary also defines the symbols used in equations.

Cosmic Periodic Table: The authors have put together a periodic table that shows a wide variety of important astronomical information about the elements, including their origins, abundance, and condensation temperatures. To make this easier to read, the table is now printed in a foldout format.

Star Charts: A good star chart helps link the study of astronomy to the night sky. *Pathways to Astronomy* offers a foldout star chart of the equatorial region as well as polar charts and seasonal star charts for Northern-Hemisphere observers. These can help you explore the night sky. The charts show the location of the Messier objects and several other bright deep-sky objects that can be found with a small telescope or binoculars. The foldout chart is also useful for observing projects, such as tracking the positions of the Moon and planets.

Unit Elements As you read each Unit, there are a number of features designed to help you gain mastery of the material, including links to materials outside of the book and cross-references to help you gain a broader understanding of the material.

Explore what you can see in the night sky!

Clarification Point

Some widely held beliefs about astronomy are known to be incorrect!

Concept Question

These questions invite you to think about ideas that go beyond the text.

Mathematical Insight

These marginal notes explore the mathematics of the text more deeply.

Cosmic Frontiers

A place to note upcoming missions and interesting research directions.

Learning Objectives: At the start of each Unit, a list of learning objectives describes the most important skills and abilities that readers should strive for in studying that Unit. These identify specific actions (such as describing, explaining, comparing, and calculating) that demonstrate a good mastery of the material.

Looking Up Icons: These marginal notes point out objects that can be seen in the Looking Up figures. Use these to gain a clearer idea of how the textual descriptions relate to objects visible in the night sky. Most of these can be seen with the unaided eye or with binoculars.

Animation, Interactive, and Project Icons: A number of online resources are available through Connect. We have placed icons next to the relevant text directing you to these resources. ***Animations*** show short clips that illustrate a process that may be otherwise difficult to visualize. ***Interactives*** allow you to manipulate parameters and gain a better understanding of topics such as blackbody radiation, the Bohr model, retrograde motion, and the H-R diagram by watching the effects of these manipulations. ***Projects***, new for this edition, were designed to delve into a wide variety of astronomical phenomena using *Stellarium* software. Each project provides detailed instructions and asks probing questions as you observe events from Earth and other locations. These might be carried out as individual projects or presented in class.

Clarification Points: *Un*-learning a preconceived notion is one of the most challenging problems facing the student of astronomy. Marginal notes call attention to common misunderstandings that we have encountered. These points of confusion can be particularly difficult to overcome, so they deserve special attention.

Concept Questions: Hundreds of Concept Questions are scattered throughout the margins of the Units. These questions are designed to invite readers to think beyond the text and to ponder questions that have no easy answer. Many also make good group discussion questions.

Mathematical Insights: These marginal notes provide mathematical details to clarify the discussion in the text or expand beyond it. Derivations of some mathematical formulas, as well as worked examples of mathematical problems and insights into mathematical thinking, are placed in these boxes.

Cosmic Frontiers: We added these boxes to highlight anticipated results from ongoing projects, upcoming spacecraft missions, and speculative material that is not yet "ready for primetime," but is interesting nevertheless!

Key Points and Key Terms: At the end of each Unit, Key Points are summarized and Key Terms (which are shown in bold in the text) are cross-referenced to where they first appear. Reviewing the key points and terms may provide useful reminders of the important points covered in the Unit. Definitions for Key Terms are provided in the glossary.

End-of-Unit Questions: In addition to the Concept Questions, which are cross-referenced at the end of each Unit, we provide Review Questions, Quantitative Problems, and Test Yourself multiple-choice questions. Each type of question is designed for a different purpose. The Review Questions provide an opportunity to check your recollection of basic facts and ideas that are directly covered in the text. The quantitative problems take a step beyond basic comprehension and challenge you to carry out calculations related to the Unit's topic. Some of these problems are difficult, but all can be solved using the ideas and formulas presented in the book. The Test Yourself questions are structured to test your understanding of concepts as well as knowledge of important facts. To get the most out of these questions, write down your answers before checking the answers provided at the end of the book.

FOR THE INSTRUCTOR

A number of instructor resources are available through our Connect platform. These include:

- **Test Builder in Connect** Available within Connect, Test Builder is a cloud-based tool that enables instructors to format tests that can be printed or administered within an LMS. Test Builder offers a modern, streamlined interface for easy content configuration that matches course needs, without requiring a download.

  Test Builder allows you to:

  - access all test bank content from a particular title.
  - easily pinpoint the most relevant content through robust filtering options.
  - manipulate the order of questions or scramble questions and/or answers.
  - pin questions to a specific location within a test.
  - determine your preferred treatment of algorithmic questions.
  - choose the layout and spacing.
  - add instructions and configure default settings.

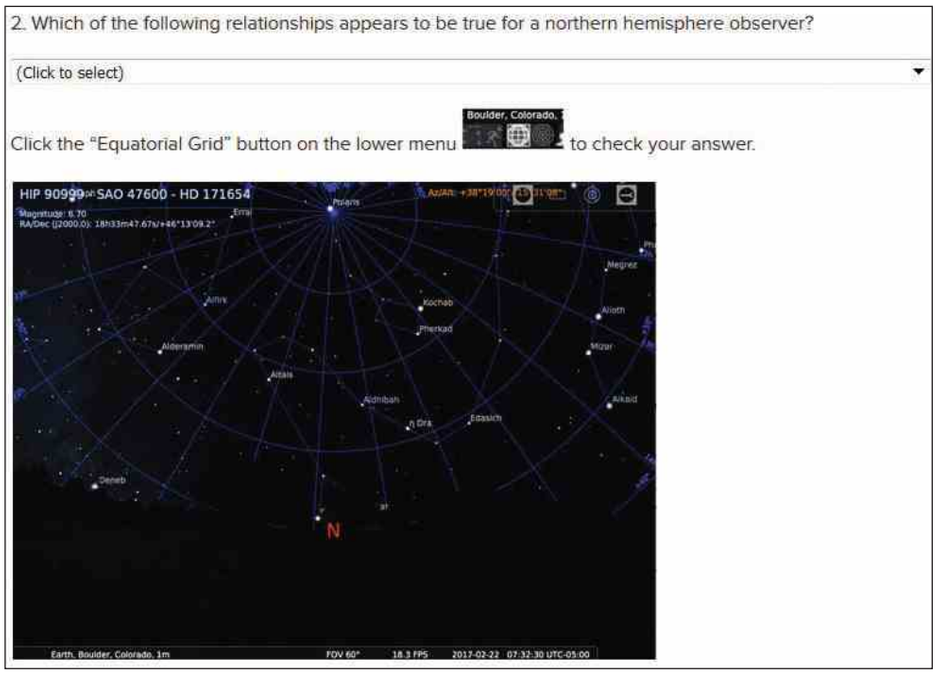
  Test Builder provides a secure interface for better protection of content and allows for just-in-time updates to flow directly into assessments.

- **Presentation Tools** Accessed through *Pathways* Connect site, the Presentation Tools are an online digital library containing assets such as photos, artwork, animations, and other media types that can be used to create customized lectures, visually enhanced tests and quizzes, compelling course websites, or attractive printed support materials. Assets are copyrighted by McGraw-Hill Higher Education, but they can be used by instructors for classroom purposes. The visual resources in this collection include:
  - **Art** Full-color digital files of all illustrations in the book can be readily incorporated into lecture presentations, exams, or custom-made classroom materials. In addition, all files are preinserted into PowerPoint© slides for ease of lecture presentation.
  - **Photos** The photos collection contains digital files of photographs from the text, which can be reproduced for multiple classroom uses.
  - **Animations and Interactives** Numerous full-color animations and the astronomy interactives, illustrating important processes, are also provided.
  - **Projects** Designed for individual or classroom use, the projects provide step-by-step instructions for viewing astronomical phenomena using *Stellarium* software.
  - **PowerPoint Lecture Outlines** Ready-made presentations that combine art and lecture notes are provided for each Unit of the text.

Also residing on your textbook's Connect site are:

- **Instructor's Manual** The Instructor's Manual is housed within the Connect site and can be accessed only by instructors. This manual includes solutions to the quantitative questions at the end of chapter.

- ***Stellarium* Exercises** These exercises can be assigned through Connect and used with the *Stellarium* open-source planetarium software. Students will explore the sky through this dynamic tool and answer questions about their experience to reinforce the concepts in the text.



From *Stellarium* Exercises in Connect.

ACKNOWLEDGMENTS

Writing and revising a text such as *Pathways* is a collaboration with everyone who reads or uses it. We are deeply grateful to everyone who offered a suggestion, pointed out a mistake, or found a place where we might improve the content. Our sincere thanks to all the reviewers who have offered suggestions throughout the life of this book. Special thanks to those who were instrumental in the preparation of SmartBook 2.0 for *Pathways to Astronomy* as well as to those who helped develop and enhance our online homework offerings in Connect.

Finally, the authors would like to thank the team at McGraw-Hill for all their assistance with updating *Pathways,* including Megan Platt, Shannon O'Donnell, Laura Bies, Lorraine Buczek, and Beth Blech. Thanks particularly to copyeditor John S. Murdzek for a close reading of the revised manuscript and many corrections and suggestions for improvement.