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

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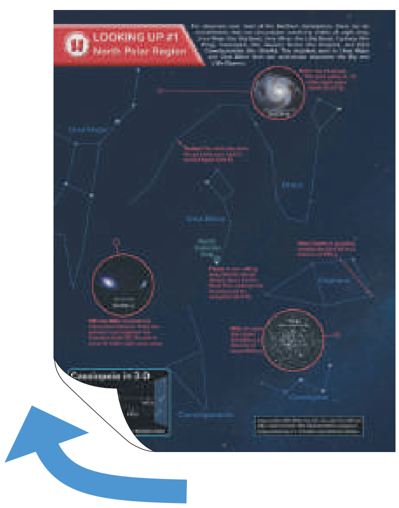
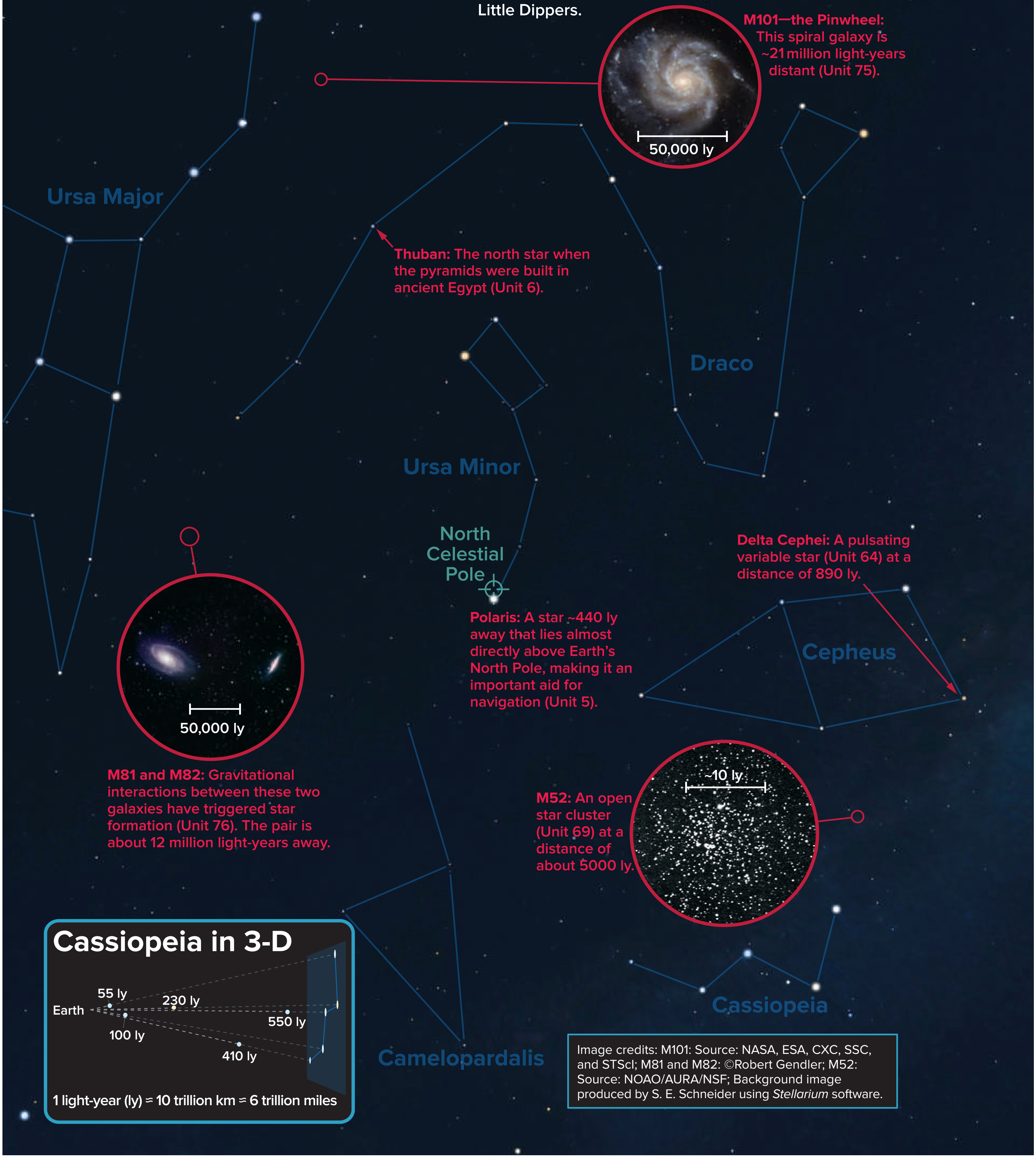


Looking Up at the night sky is one pathway to astronomy. The beauty of the night sky, the pattern of stars in their ancient constellations, invites us to wonder about our place in the universe. A small telescope shows even more remarkable sights, and further study reveals exotic and violent phenomena 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 • LOOKING UP •

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.



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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

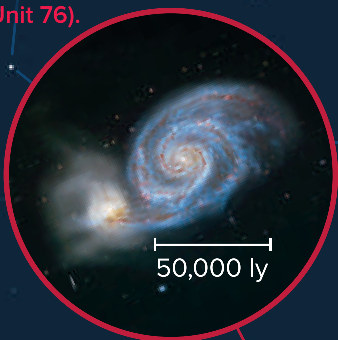
Draco

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)

Ursa Major

pointer stars

Big Dipper

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

Boötes

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).

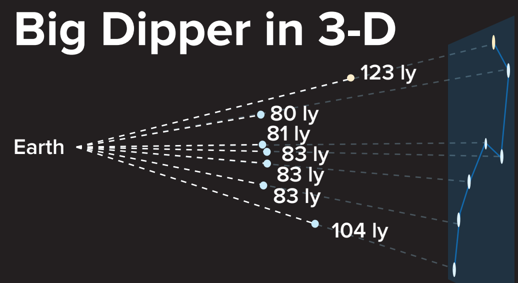
Follow the arc of the Big Dipper's handle to Arcturus

Leo Minor

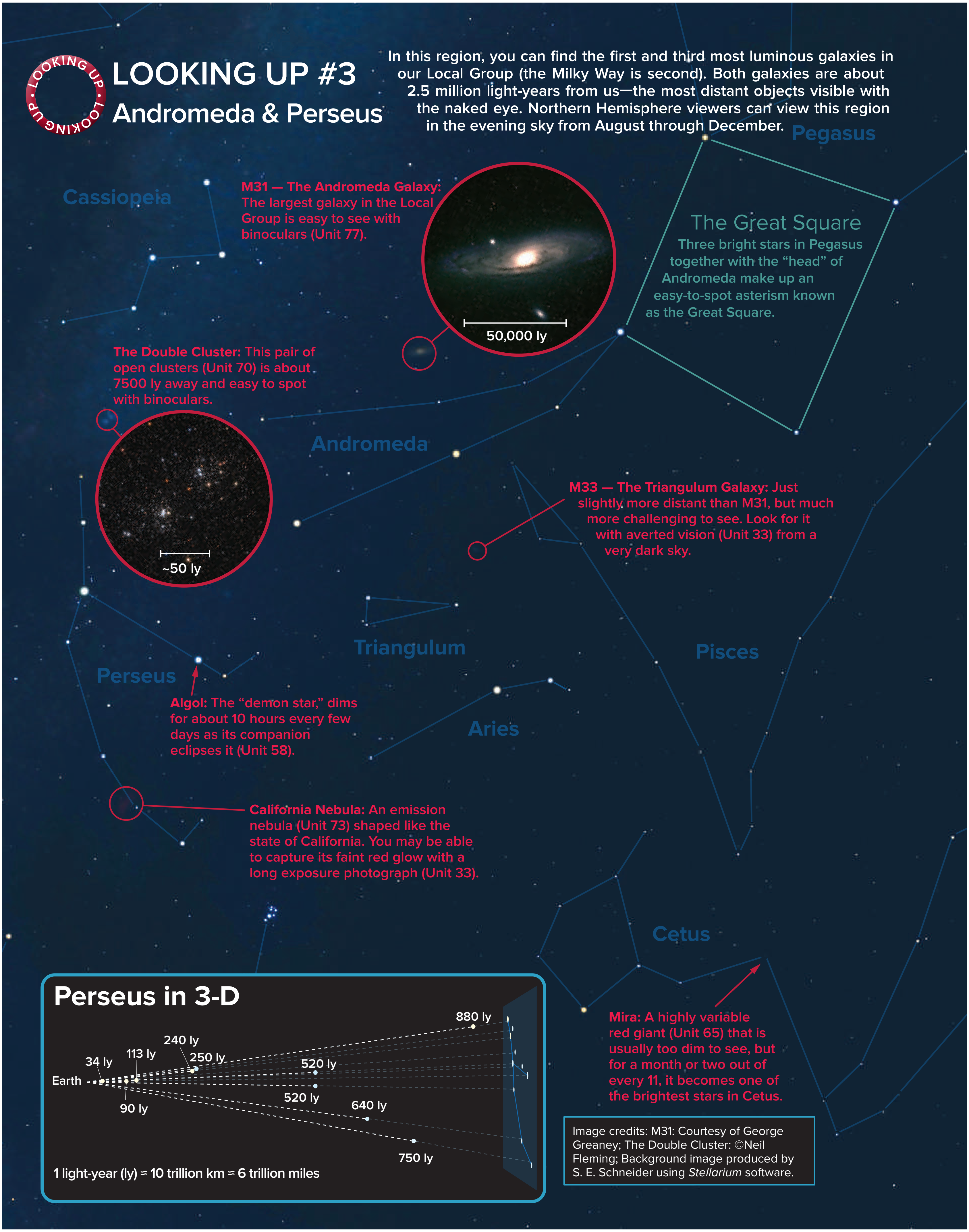
Arcturus: A red giant (Unit 63) that is 37 light-years distant.

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.

Big Dipper in 3-D



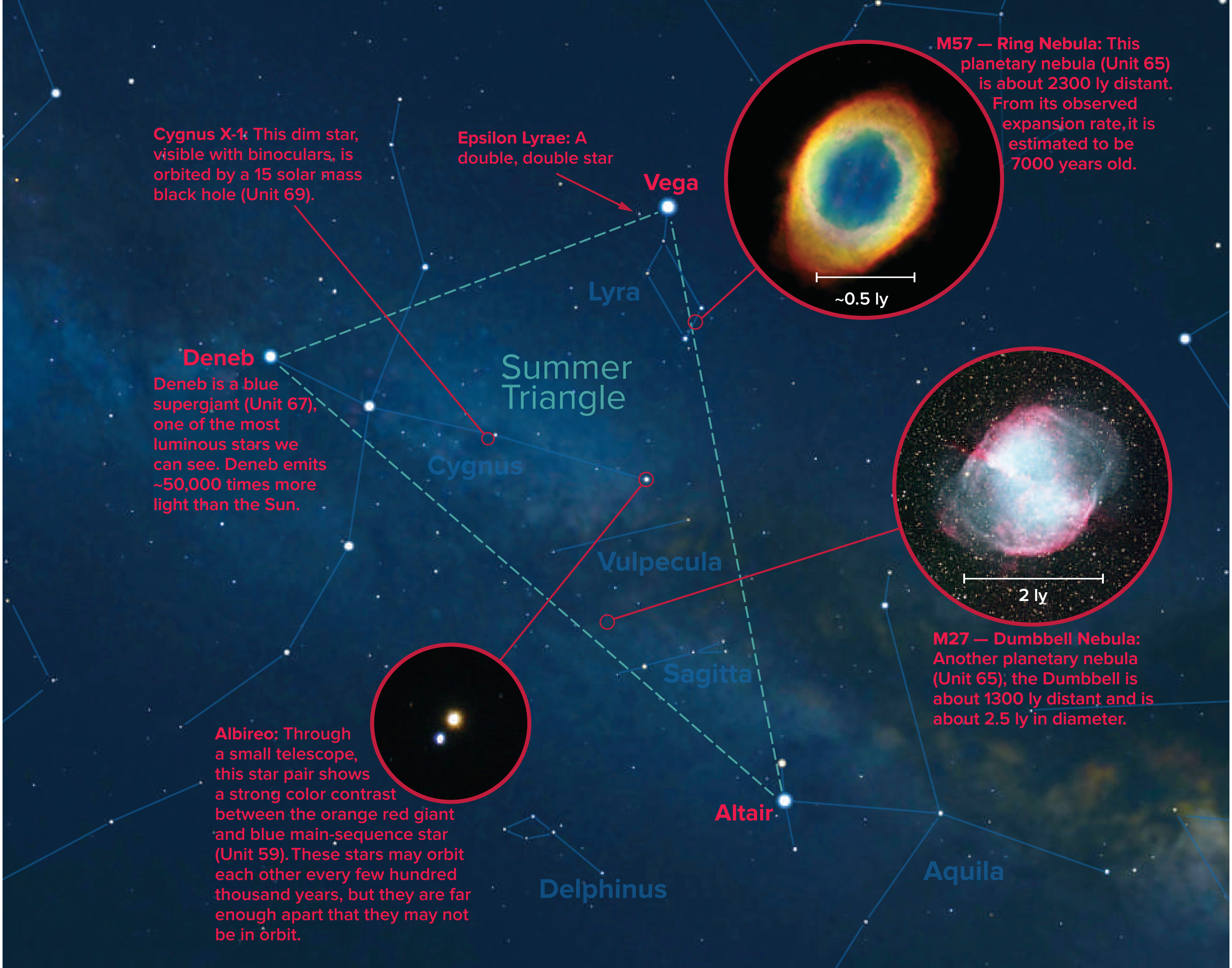
1 light-year (ly) = 10 trillion km = 6 trillion miles


LOOKING UP
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).
50,000 ly
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
~50 ly
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
Perseus in 3-D
880 ly
240 ly
34 ly
113 ly
250 ly
520 ly
Earth
90 ly
520 ly
640 ly
750 ly
1 light-year (ly) = 10 trillion km = 6 trillion miles
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.
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

LOOKING UP • LOOKING UP •

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.



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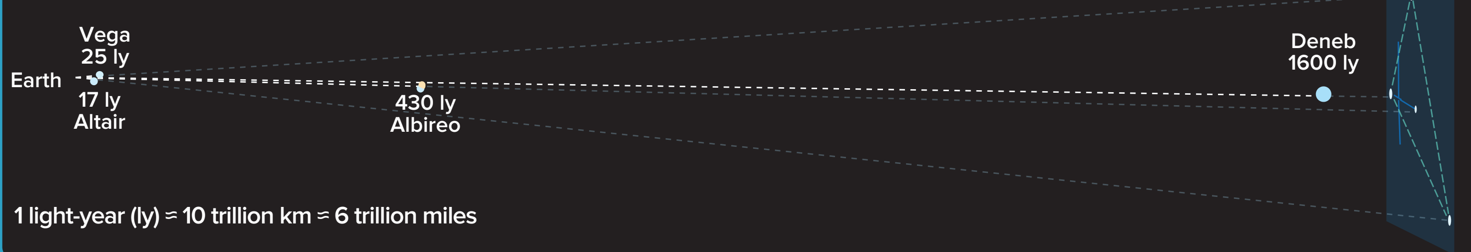
The Summer Triangle in 3-D



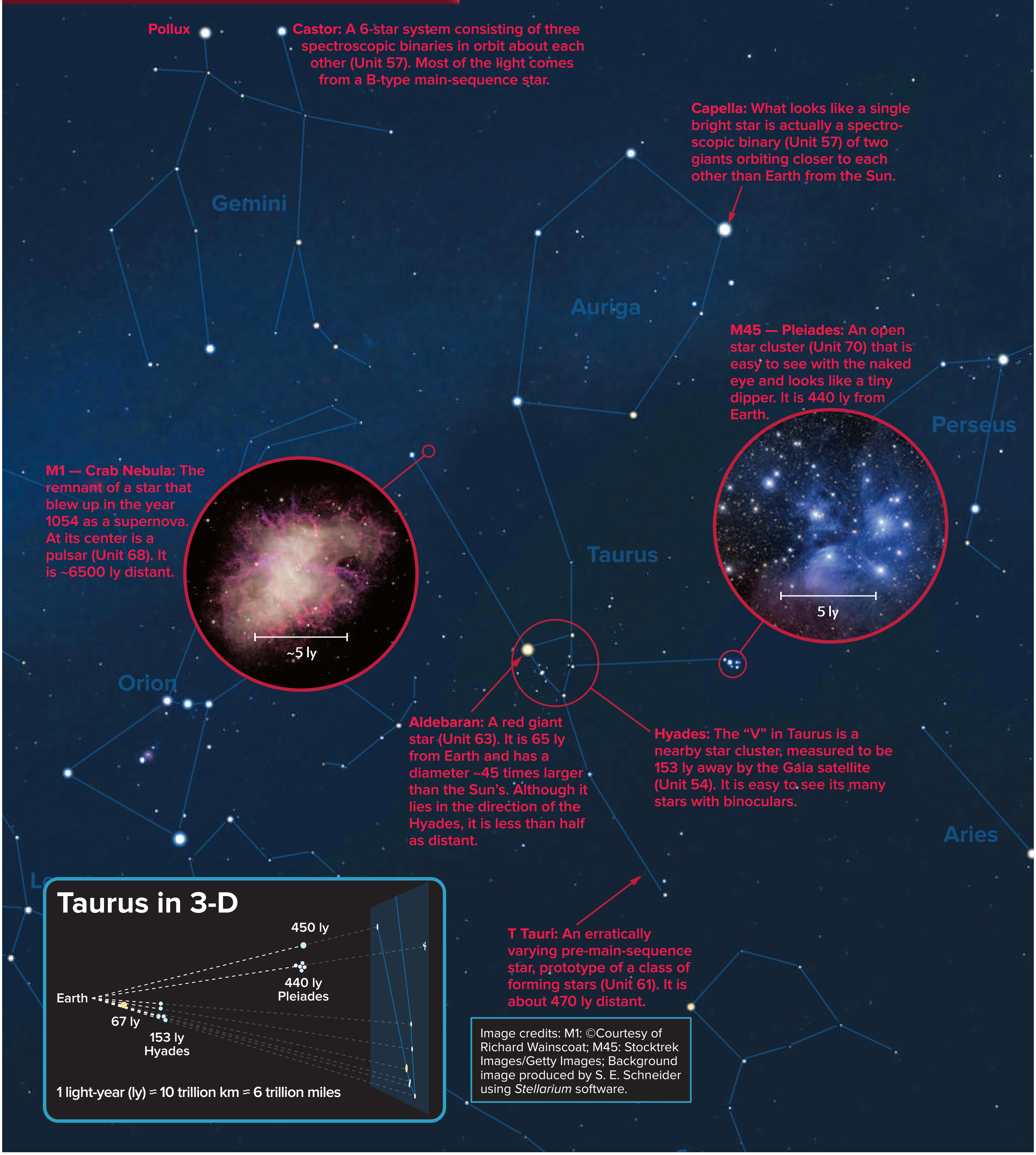
1 light-year (ly) ≈ 10 trillion km ≈ 6 trillion miles

LOOKING UP #5

Taurus

LOOKING UP • LOOKING UP •

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.



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.

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.

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.

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.

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

Taurus in 3-D

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

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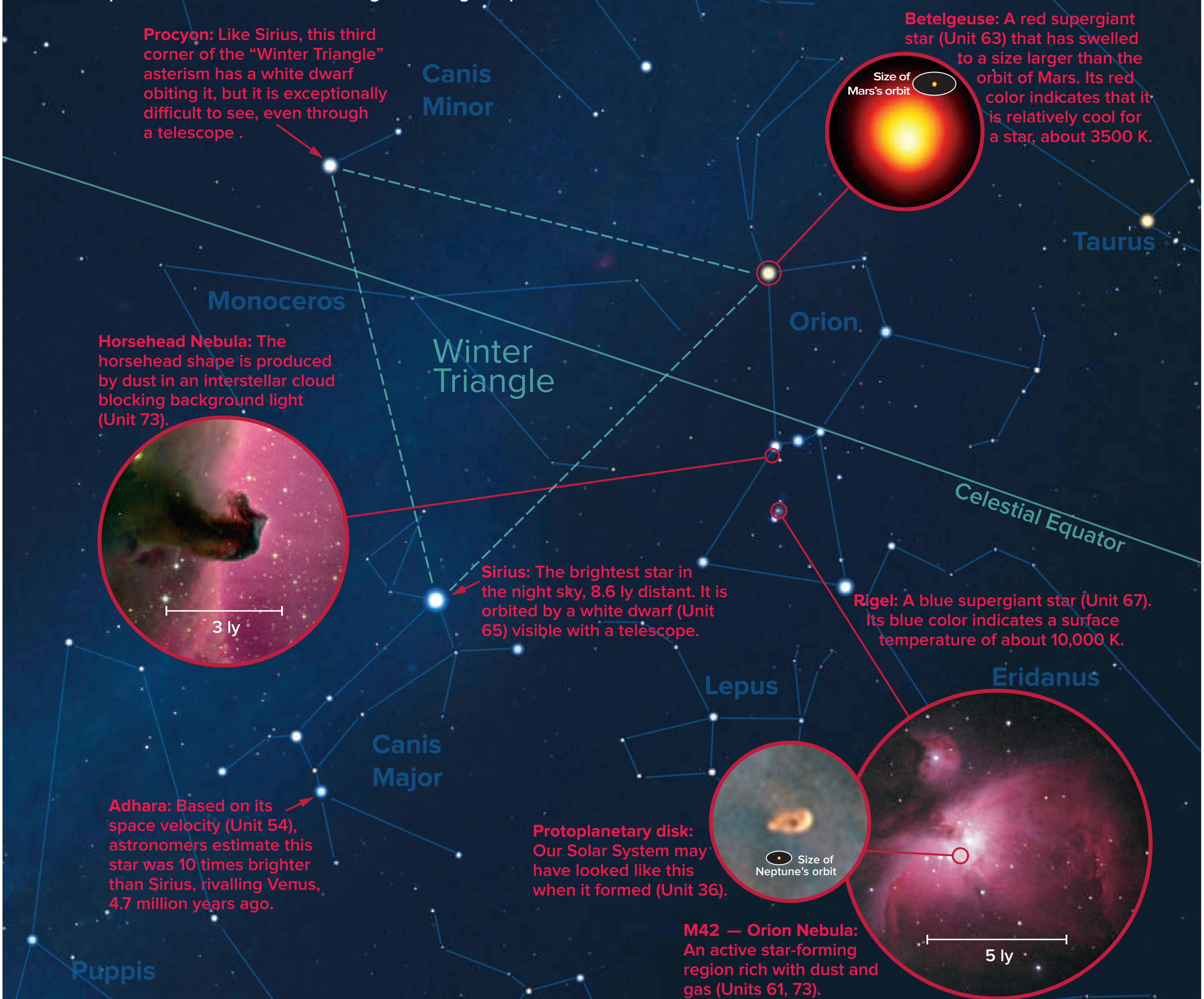
LOOKING UP #6
The Winter Triangle

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 .

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.

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

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.

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).

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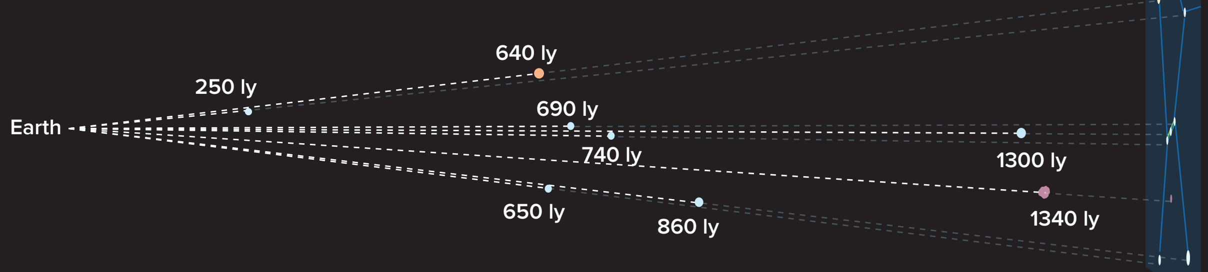
Orion in 3-D

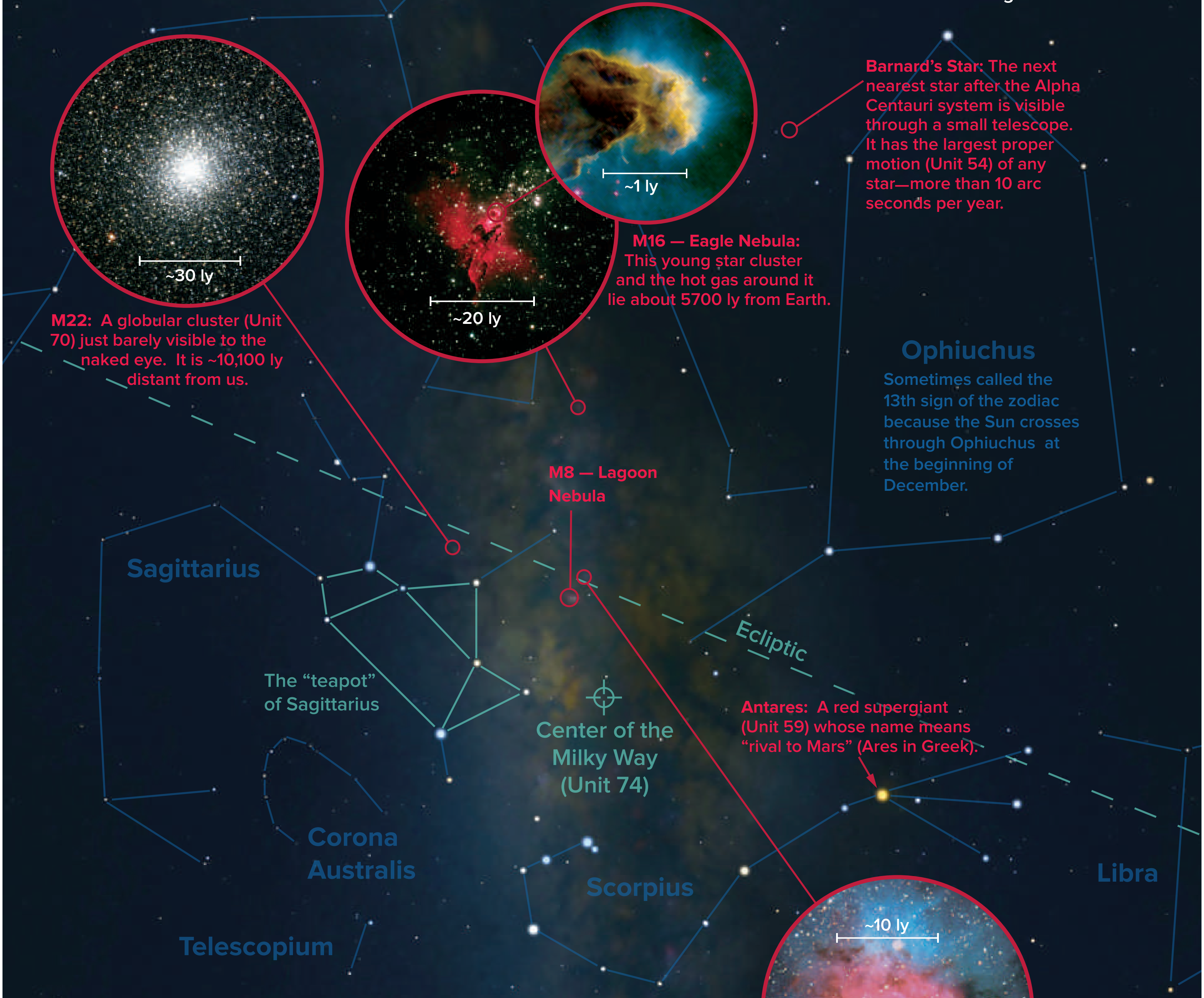


1 light-year (ly) ≈ 10 trillion km ≈ 6 trillion miles

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.



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.

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

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

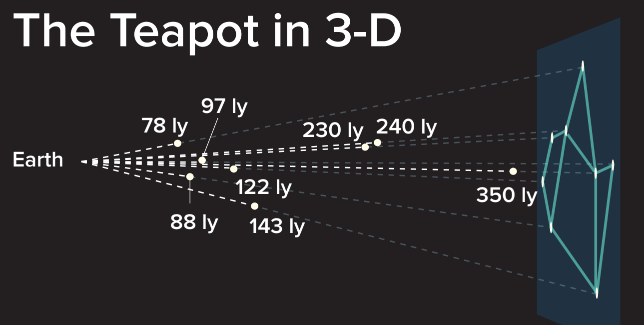
M8 — Lagoon Nebula

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

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

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

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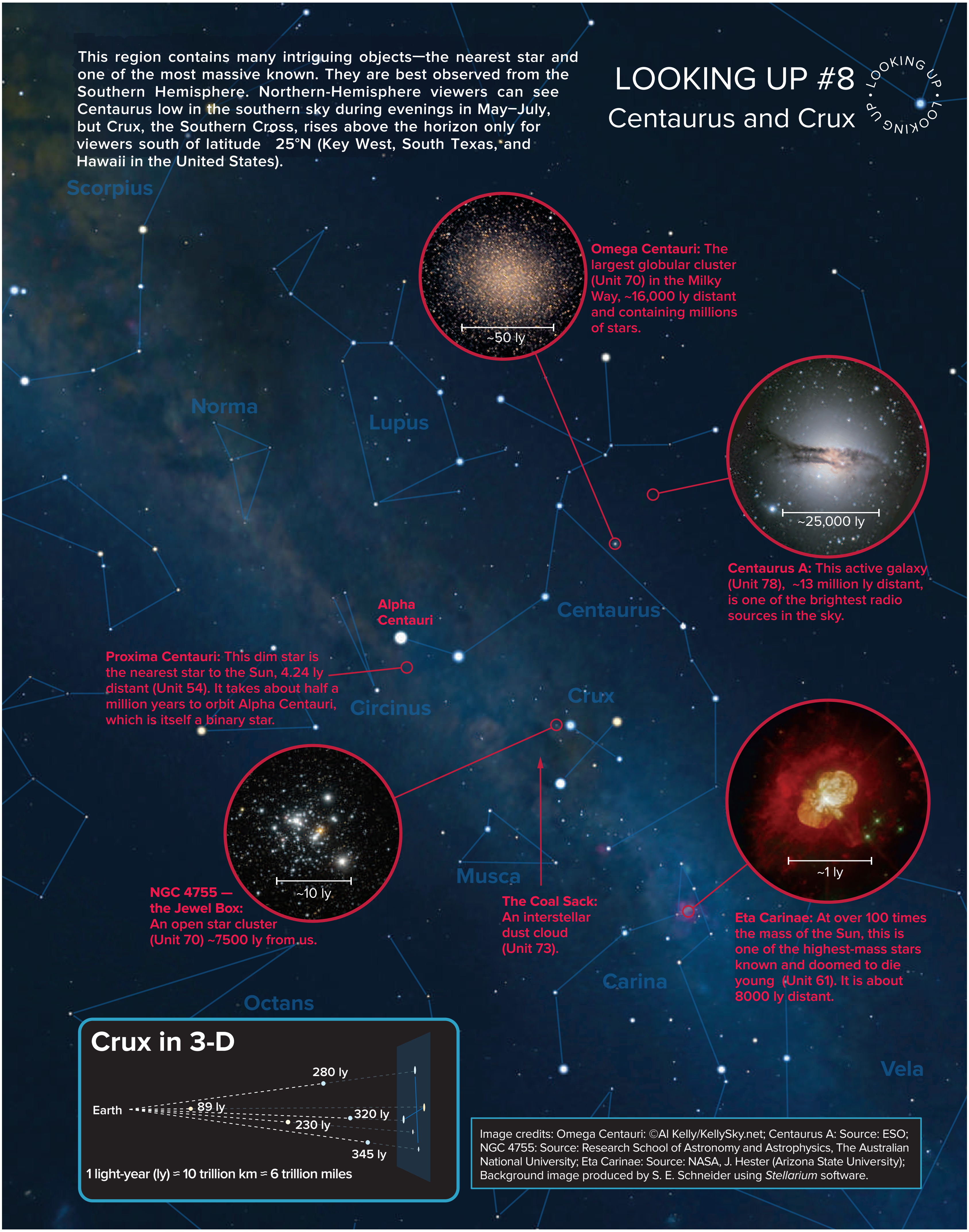
LOOKING UP #8

Centaurus and Crux

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).



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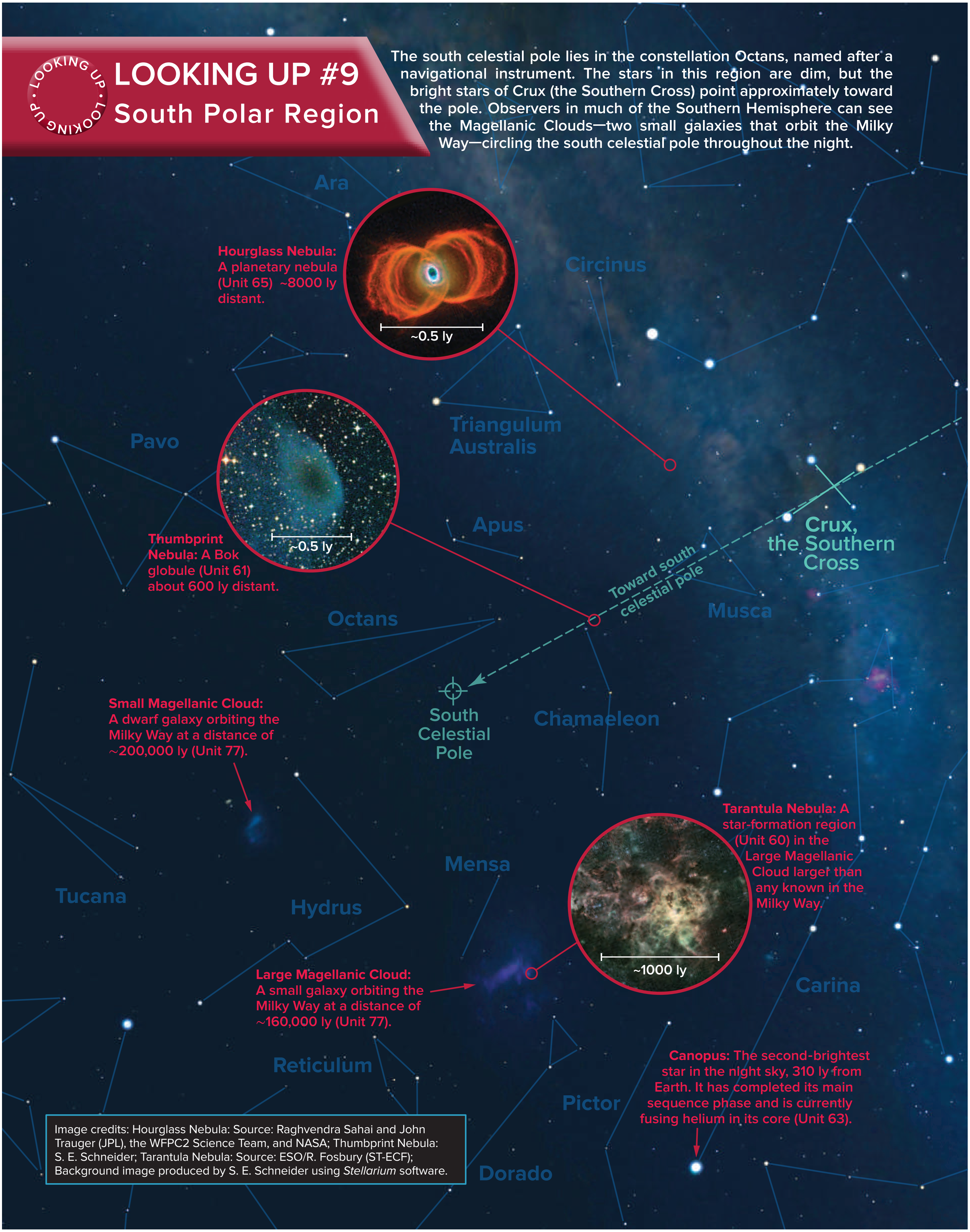
LOOKING UP #9
South Polar Region

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.



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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.

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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.

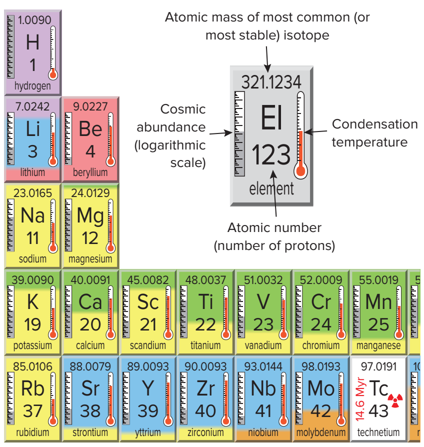
The Unit format also provides an opportunity to take some extra steps beyond the ordinary text. The authors have included some material of special interest that most introductory texts do not offer—for example, Units on calendar systems and special relativity. Units like these might be assigned for independent 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

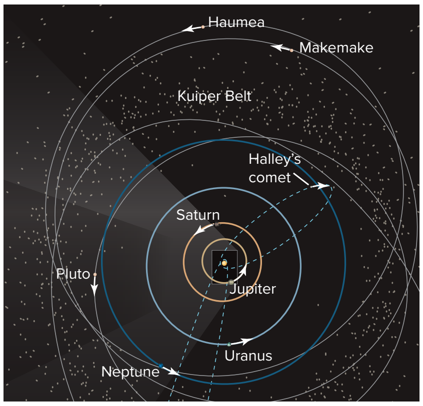
For every new edition, we scan the literature and popular press to include the most interesting recent results. The excellent suggestions of readers and reviewers are also much appreciated for updates and improvements to *Pathways*. One of the more challenging aspects of revising the text is that we 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.

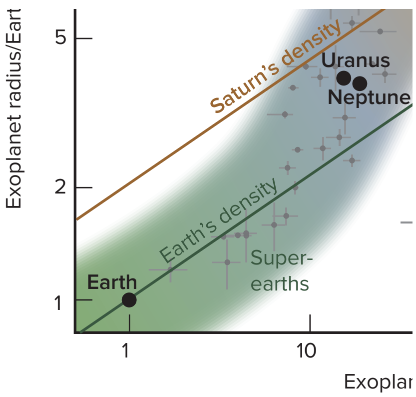
The Unit topics remain the same as for the past three editions, with the most significant updates to individual Units noted here. We also made a few broad changes that extend beyond individual Units:



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.

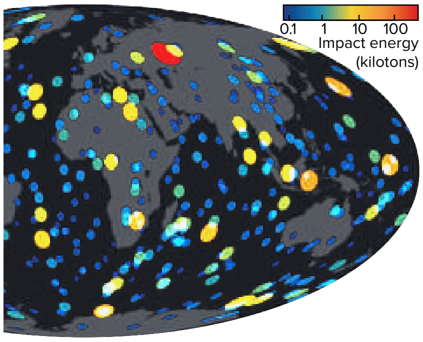
Unit 43 Asteroids: New image and discussion of early results from asteroid sample-return missions by JAXA and NASA.

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.

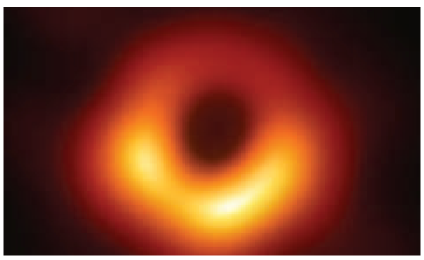
Unit 69 Black Holes: Added discussion of range of black hole masses detected by LIGO.

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.

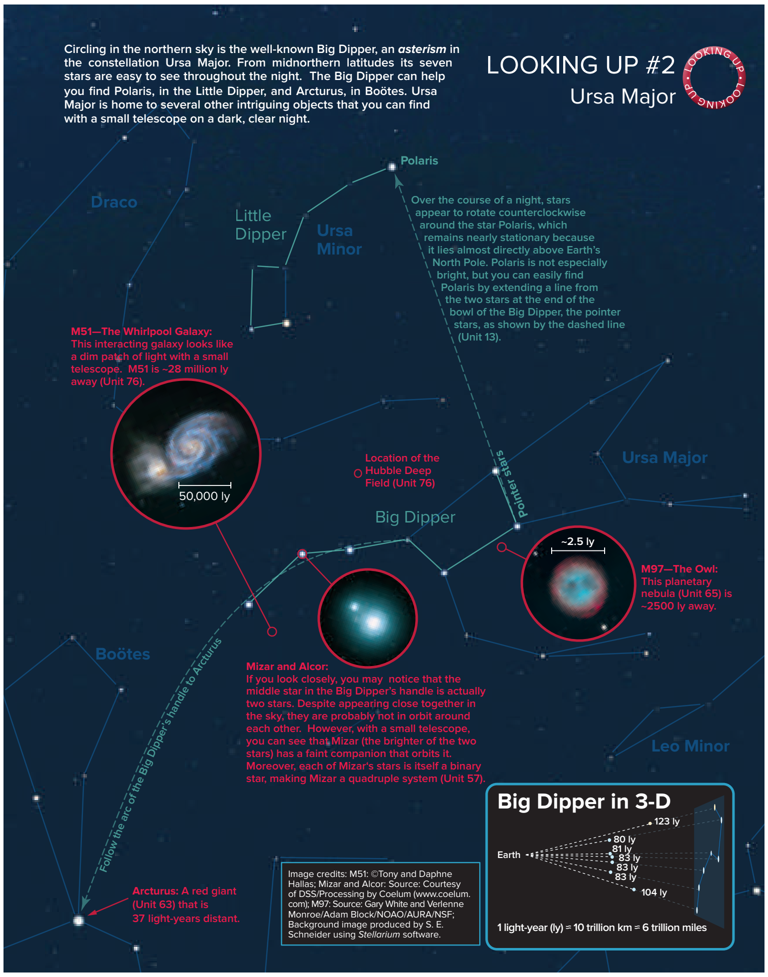
Unit 81 The Edges of the Universe: Improved illustration of cosmic horizon for different observers.

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.

LOOKING UP ART

Explore what you can see in the night sky!

ANIMATIONS ILLUSTRATE PROCESSES

INTERACTIVES PROBE CONCEPTS

PROJECTS EXPLORE THE 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.

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- **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:
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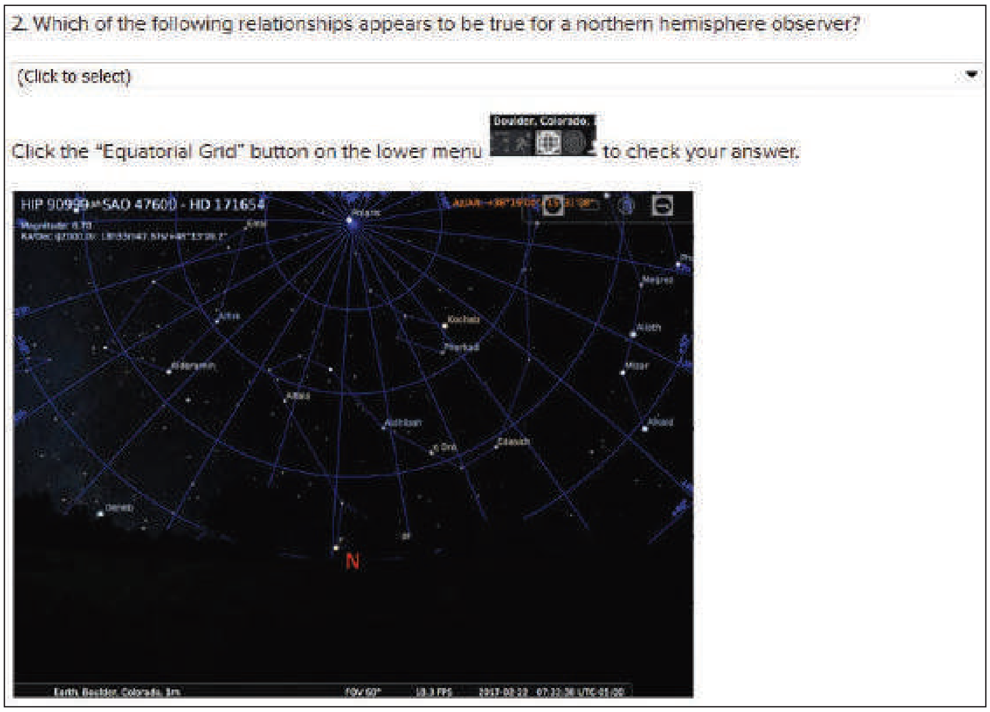
  - **Animations and Interactives** Numerous full-color animations and the astronomy interactives, illustrating important processes, are also provided.
  - **Projects** Designed for individual or classroom use, the projects provide step-by-step instructions for viewing astronomical phenomena using *Stellarium* 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.

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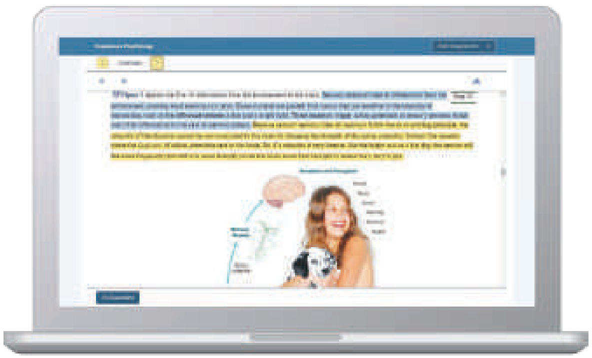

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PART 1

UNIT 1

Our Planetary Neighborhood

1.1 Earth
1.2 The Moon
1.3 The Planets
1.4 The Sun
1.5 The Solar System
1.6 The Astronomical Unit

Part 1 Photo Credit: Stocktrek Images/Getty Images

Learning Objectives

Upon completing this Unit, you should be able to:

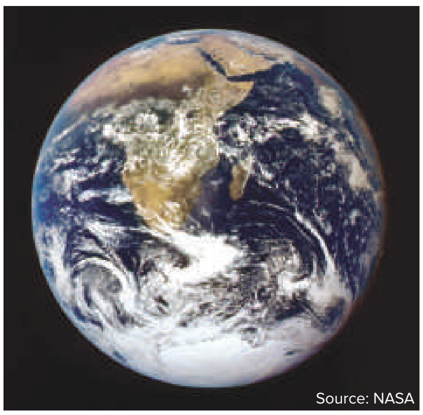
- List the kinds of objects that reside in our Solar System.
- Relate sizes of the Sun, planets, and other objects in the Solar System to the size of Earth.
- Define the "astronomical unit," and relate the distances between objects in the Solar System to their sizes.

Astronomy is the study of the universe: from Earth itself to the most distant galaxy, from deciphering its nature at the beginning of time to predicting its eventual fate in the remote future. Within the vast space of the universe lie planets with dead volcanoes whose summits dwarf Mount Everest. There are stars a thousand times the size of the Sun—so large that in the Sun's place, they would swallow up Earth. And there are galaxies—slowly whirling systems of billions of stars—so vast that Earth is smaller by comparison to them than a single grain of sand is to Earth itself. On this small planet within this immense cosmic landscape, life has evolved over billions of years, giving rise to creatures who seek to understand the nature of the universe.

Through astronomy we gain the ability to study places so remote that there is no possibility of our ever visiting them. We gain insights into alien environments unlike anything found on Earth. And our insights provide new perspectives on our home planet and about ourselves.

The vast variety of planets, their distances, and their sizes are almost unimaginable. We will explore Earth and its neighboring planets in detail in Part III; but to gain some sense of scale, we begin in this Unit with a brief look at Earth and its neighborhood—the Solar System. We proceed from the familiar to the less familiar, introducing some of the common terms astronomers use and examining how astronomers speak of the huge distances between the planets.

1.1 EARTH



Source: NASA

FIGURE 1.1 The planet Earth, our home, with blue oceans, white clouds, and multihued continents. This photo was taken by *Apollo 17* astronauts traveling to the Moon in 1972.

We begin with Earth, our home **planet** (Figure 1.1). This spinning ball of rock and metal, coated with a thin layer of gas and liquid, is huge by human standards, but it is one of the smaller bodies in the cosmic landscape. Nevertheless it is an appropriate place to start, because as the base from which we view the universe, it determines what we can see. We cannot travel to any but the nearest objects in our quest to understand the universe. Instead, we are like children who know their neighborhood well but for whom the larger world is still a mystery, known only from books and television.

But just as children use knowledge of their neighborhood to build their image of the world, so astronomers use their knowledge of Earth as a guide to distant worlds. The size of Earth and features on it, for example, are useful reference points for appreciating the sizes of other objects. We will often refer to other planets in terms of their radii relative to Earth's own radius of about 6371 kilometers (3959 miles). Similarly, it is convenient to refer to other planets' masses in terms of Earth's own mass, which is itself so large that it is difficult to imagine: 5,970,000,000,000,000,000,000,000 kilograms, or about 6 billion trillion tons.

Although few people realize it, we use the size of Earth for defining the meter, the fundamental unit of the **metric system** (see Unit 3). The meter was originally defined to be one 10-millionth of the distance from the equator to the North Pole. The measurements made in the late 1700s were slightly off, but Earth's circumference very nearly equals 40,000 kilometers (about 25,000 miles). When this system was introduced, it was a convenient way to measure the distances ships traveled on Earth's oceans, and it offered a less arbitrary standard than the many other measurement systems used at the time.

The internal heat of planets comes from two main sources—heat left over from their formation and the decay of radioactive elements in their interior (Unit 35). Their ability to retain this heat depends mostly on their size.

The geological processes that occur on Earth provide another kind of measure—one for interpreting the processes that shape the other planets. When a volcano spews molten lava, it provides a hint that below the surface our planet is extremely hot. During the last century, geologists discovered that this internal heat drives slow but powerful currents that shake our planet's crust, move continents, build mountains, and heave up volcanoes. We can carry over our understanding of such geological processes here on Earth to help us make hypotheses about the processes that create similar features on other planets. And when we discover different features on other worlds, we can use them to help us think about Earth in new ways.

1.2 THE MOON

Our nearest neighbor, the Moon, is a world profoundly different from Earth. The Moon is our **satellite,** orbiting Earth nearly 400,000 kilometers (about a quarter-million miles) away. A string stretched from Earth to the Moon could wrap around Earth almost 10 times. The Moon is much smaller, having a diameter only about one-quarter our planet's. The Moon also has symbolic significance for us—it marks the present limit of direct human exploration of space.

FIGURE 1.2 (A) The Moon as we see it with unaided eyes. (B) The Moon through a small telescope. (C) *Apollo 17* astronauts on the Moon's surface.

With the naked eye, the Moon appears to be a quiet, glowing orb (Figure 1.2 A); but with a small telescope or binoculars, we can see that the Moon is somewhat like Earth in having mountains and plains on its surface—yet utterly unlike Earth as well (Figure 1.2 B and C). Instead of white whirling clouds, green-covered hills, and blue oceans, we see an airless, pitted ball of rock. Instead of mountain ranges and volcanoes, the Moon's surface is peppered with circular craters blasted into the surface where bodies crashed into it. We see evidence of a history of steady pounding by objects ranging from the microscopic to the size of mountains, impacting at speeds more than 10 times faster than any rifle bullet. Some of the larger collisions carved out craters more than 100 kilometers (60 miles) in diameter, and innumerable smaller impacts pulverized surface rock to rubble and dust.

Earth, so near to the Moon in space, must have suffered a similar pounding, yet looks utterly different. Why are these two worlds so different? Much of the explanation lies in their greatly different mass. The Moon's mass is only about 1/80th Earth's, and its smaller bulk made the Moon less able to retain internal heat or an atmosphere after its formation. With less internal heat, the Moon's interior is quiet. Heat-driven motion, so important in shaping and changing Earth's

Concept Question 1

How do you imagine people's perceptions of the heavens might have changed after seeing the Moon through the first telescopes in the early 1600s?

surface over the eons, is nearly absent in the Moon. Without an atmosphere, the Moon is not protected from small impacting objects, which on Earth are vaporized through the heat of friction before reaching the ground. And without erosion caused by an atmosphere or modification of the surface caused by geological activity, the Moon's surface exhibits all of its old scars. Much of the record of Earth's past has been erased, but the Moon can help us reconstruct our planet's ancient history.

1.3 THE PLANETS

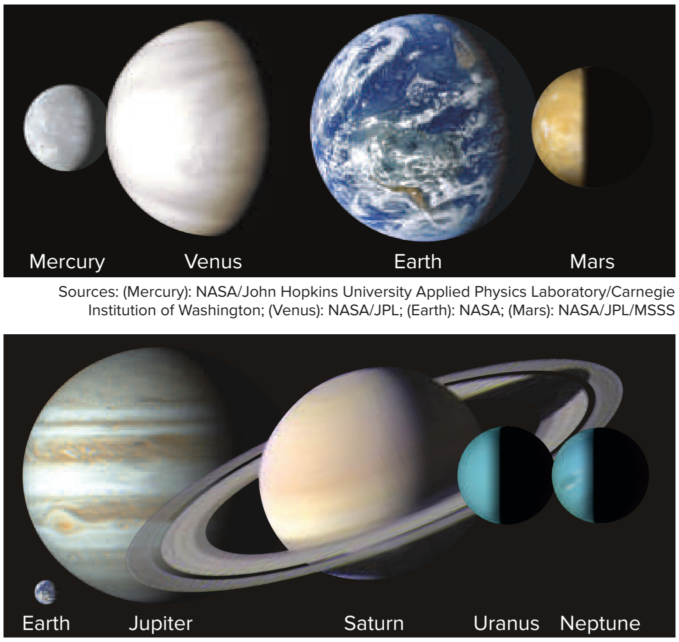
Beyond the Moon, orbiting the Sun as Earth does, are seven other planets, sister bodies of Earth. To the unaided eye, the other planets are mere points of light whose positions shift slowly from night to night. But by observing them, first with Earth-based telescopes, then ultimately by remotely piloted spacecraft, we have learned that they are truly other worlds.

In order of increasing distance from the Sun, the eight planets are Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune. These worlds have dramatically different appearances, as illustrated in Figure 1.3. The surfaces of the planets differ enormously from the landscape of Earth. Craters scar the airless surface of Mercury, while dense clouds of sulfuric acid droplets completely shroud Venus. Huge canyons, volcanoes, and deserts spread across the ruddy face of Mars.

The correct relative sizes of the planets are difficult to show in a single figure because the four inner planets are so much smaller than the four outer planets. All four outer planets have atmospheres so vast they could swallow Earth whole. Jupiter has storm systems that are as big as Earth. These giant planets all have ring systems, although Saturn's is the brightest by far. Uranus and Neptune are colored blue, not by water but by a deep layer of methane. Astronomers often indicate the sizes of the planets by comparing them to Earth's radius, which we abbreviate as $R_\oplus$, using the international symbol $\oplus$ for Earth. The planets range in size from Jupiter, with a radius of 11 Earth radii (11 $R_\oplus$), down to Mercury, with a radius of slightly over one-third Earth's radius (0.38 $R_\oplus$).

Our two nearest neighboring planets, Venus and Mars, provide deeper insights into our own planet because they are so similar to, and yet so different from, Earth. They are the closest to Earth in size, with radii of 0.95 and 0.53 $R_\oplus$, respectively. Their landscapes include features that resemble many seen on Earth—for example, they both have volcanoes and mountain ranges—so we conclude that geological processes like those that shaped Earth must have occurred on both.

Despite their similarities in size and in distance from the Sun, Venus and Mars have atmospheres dramatically different from Earth's. On Venus we would be crushed and cooked by its intensely hot, dense atmosphere, whereas on Mars we would suffocate and freeze. And the other worlds that astronomers have studied are even more alien. Every other planet and moon that we have found would also be hostile to human life. By studying the factors that make other planets so different from Earth, we may also begin to understand the potential consequences of our own impact on Earth.



Sources: (Mercury): NASA/John Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington; (Venus): NASA/JPL; (Earth): NASA; (Mars): NASA/JPL/MSSS

Sources: (Earth): NASA; (Jupiter, Saturn, Uranus, Neptune): NASA/JPL, adapted by S. E. Schneider

FIGURE 1.3 Images of the eight planets. The four inner planets are shown to the same scale in the upper panel, and the four much-larger outer planets are shown to the same scale in the lower panel, with Earth for comparison.

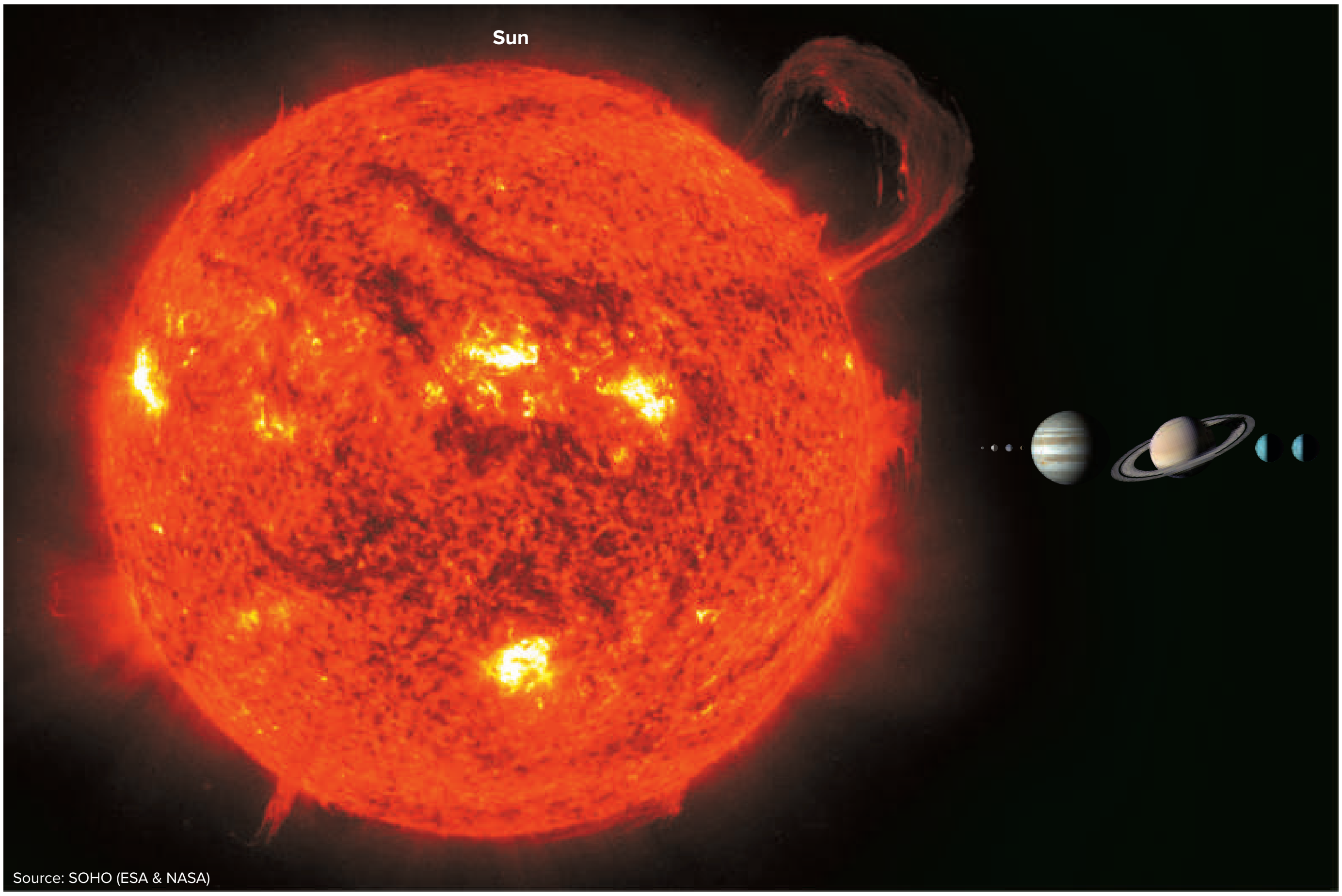


FIGURE 1.4 The Sun as viewed through a filter that allows its hot outer gases to be seen. The eight planets are shown to scale beside it for comparison. (The filter allows astronomers to see very hot helium gas.)

1.4 THE SUN

All of the planets of our Solar System are dwarfed by the Sun, whose immense gravity holds them in orbit. The Sun is a **star,** a huge ball of gas over 100 times the diameter of Earth and over 300,000 times more massive. The difference in size between the Sun and the planets is illustrated in Figure 1.4.

The Sun differs from the planets in more than just size: It generates energy in its core by nuclear reactions that convert hydrogen into helium. The Sun is producing energy at a furious rate—more in just one second than all of the bombs and the energy ever generated on Earth during human history. The energy from the intensely hot core flows to the Sun's surface, which is more than a thousand times cooler than the core but is still hot enough to vaporize iron. From there the Sun's energy streams into space, illuminating and warming the planets' surfaces.

The energy the Sun can produce is enormous but nonetheless limited. The Sun's stream of energy has already lasted more than 4 billion years—enough time for life to form and evolve on Earth and for intelligent creatures who can marvel at these things to have come into being. However, much evidence indicates that the Sun will run out of fuel eventually, in about another 5 or 6 billion years. It will then fade away like a cooling ember. Thus, astronomy helps us to look deep into the past and far into the future as we consider phenomena of an enormous range in sizes and distances.

Concept Question 2

The Sun and all the planets are hotter in their interiors than on their surfaces. What different sources of energy can you think of that might produce their internal heat?

1.5 THE SOLAR SYSTEM

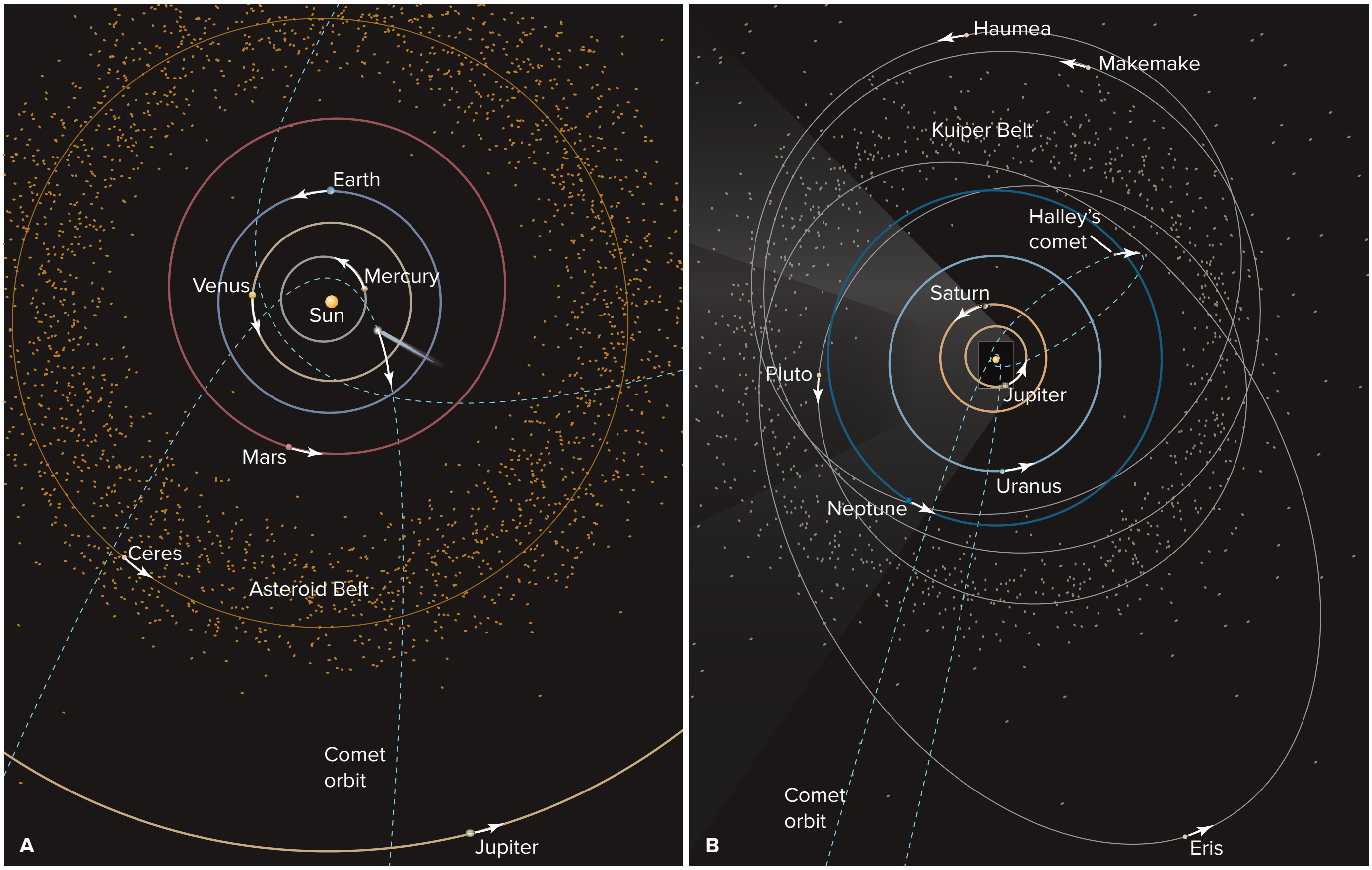
The Sun and the bodies orbiting it form the **Solar System,** bound together by the enormous gravity of the Sun. In addition to the eight planets, the Solar System is filled with a vast number of smaller bodies—satellites (moons) orbiting the planets, and asteroids and comets orbiting the Sun. However, the mass of all of the planets and other objects in the Solar System does not add up to even 1% of the Sun's mass.

The paths that the planets follow around the Sun (Figure 1.5) form a set of huge, approximately circular rings, one inside the other, with the Sun at their center. The orbits of the planets lie in nearly the same plane, so that the whole system is disk-shaped. The outermost planet—Neptune—lies about 4.5 billion kilometers (about 2.8 billion miles) from the Sun. The distances between planets in the outer Solar System are so much larger than in the inner Solar System that we have to plot these two regions separately to see them clearly.

Beyond Neptune's orbit are innumerable small objects orbiting in the "Kuiper belt," much as beyond Mars there are vast numbers of small bodies orbiting in the asteroid belt. The orbits of these objects are generally less circular and more tilted than the planets' orbits. This is especially true of comets (Unit 49) whose orbits carry them between the inner and outer parts of the Solar System.

Pluto, which is smaller than the Moon, is no longer classified as one of the major planets, but instead is classified as a "dwarf planet" or "plutoid" (Unit 48). Under this new definition, the asteroid Ceres (Unit 43) has also been reclassified as a dwarf planet. Eris, discovered in 2005, is the most massive dwarf planet yet found, about 27% weightier than Pluto, and other dwarf planets, such as Haumea and Makemake, have also been identified orbiting in the Kuiper belt.

FIGURE 1.5 Sketch of the positions and orbits of the planets and dwarf planets in our Solar System on March 20, 2011. The orbit of Halley's comet along with another typical comet orbit are also shown. The approximate location of small bodies in the asteroid belt and Kuiper belt are indicated. To show the orbits to scale, the inner (A) and outer (B) Solar System are shown separately.



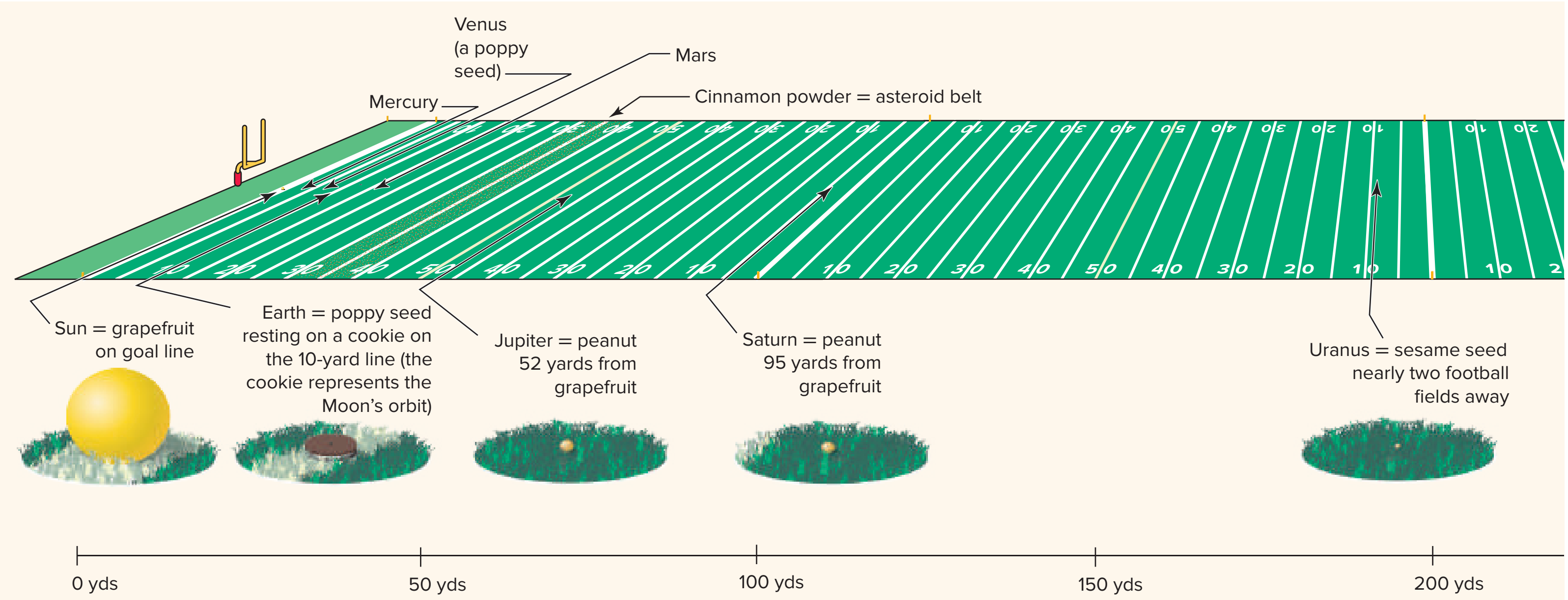


FIGURE 1.6 A scale model of the Solar System with the Sun the size of a grapefruit. At this scale, all of the planets that are visible without a telescope fit within a single football field. Uranus and Neptune each require another whole field, while Pluto, Eris, and many other icy bodies are even farther away.

1.6 THE ASTRONOMICAL UNIT

The distances between objects in the Solar System are so vast that they are almost incomprehensible. One way to picture the distances involved is to construct a scale model of the Solar System. For example, if the Sun is represented by a grapefruit, Earth would be the size of a grain of sand or a poppy seed, orbiting about 9 meters (about 30 feet) away. This scale is illustrated in Figure 1.6, where the sizes and distances of the planets are shown on a string of U.S. football fields. In this scale model, the dwarf planets would be grains of salt orbiting more than 0.35 kilometer (0.22 mile) away.

Whenever possible, we use a **unit**—a quantity used for measurement—appropriate to the size of what we seek to measure. In earlier times people used units that were quite literally at hand, such as finger widths or the spread of a hand to measure a piece of cloth, and paces to measure the size of a field. In the same tradition, although on a much different scale, astronomers have adopted Earth's distance from the Sun as a good unit for measuring the size of the Solar System. Astronomers call this distance the **astronomical unit,** abbreviated **AU.**

For several centuries astronomers did not know exactly how big an astronomical unit was. Even though they did not know how many kilometers were in an AU, they discovered ways to find out the distances to other planets in AU. For example, they could show that Mercury was about 0.4 AU from the Sun, and Neptune about 30 AU from the Sun.

Modern measurements show that the astronomical unit is about 150 million kilometers (about 93 million miles). Actually, as it orbits the Sun, Earth's distance varies from 147.1 to 152.1 million kilometers (91.4 to 94.5 million miles), just slightly different from a circle with a radius of 1 astronomical unit, as shown in Figure 1.7. The modern definition of the astronomical unit is defined in terms of the average of these extremes and has been very precisely measured as 149,597,870.7 kilometers.

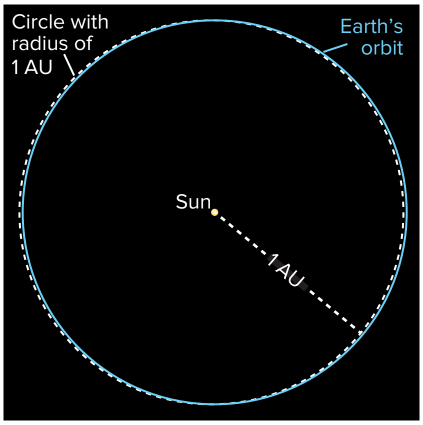
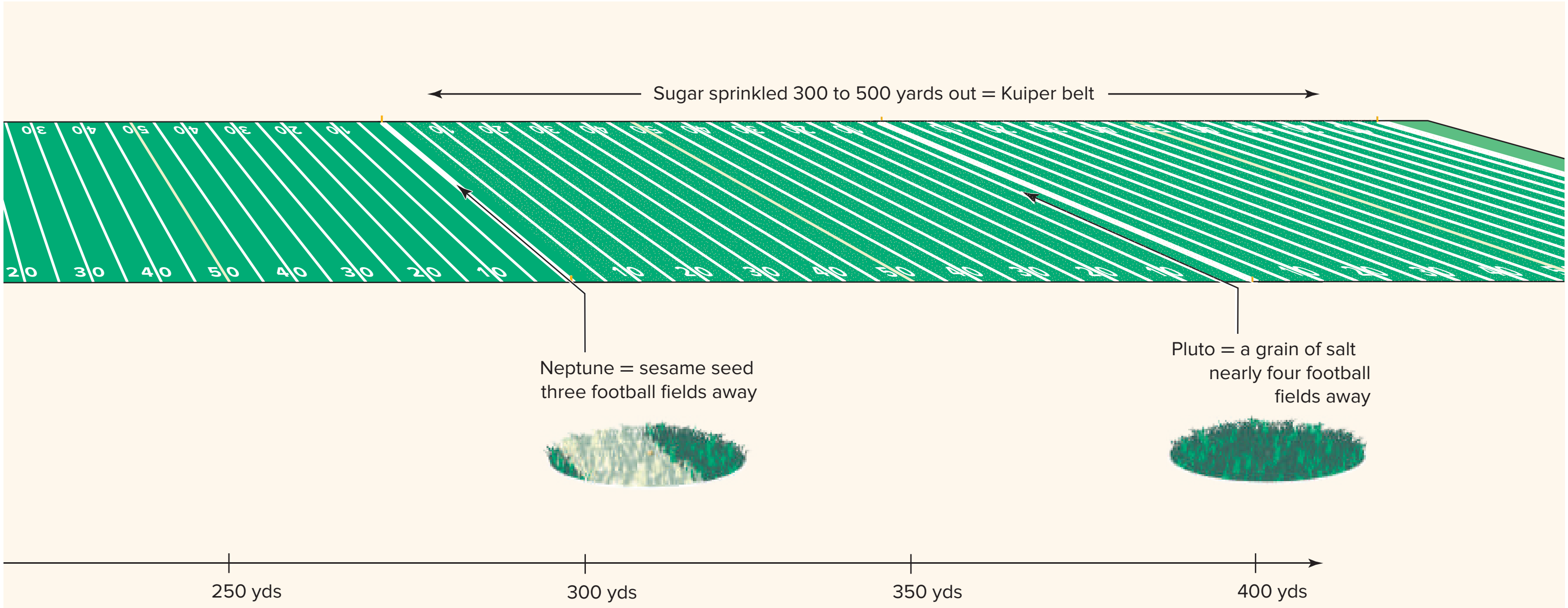


FIGURE 1.7 Earth's orbit (shown in blue) is nearly a circle of radius 1 astronomical unit (dotted white circle); however, the distance from the Sun is about 3% larger at its maximum than at its minimum.

Concept Question 3

What do you suppose are the effects of the varying distance of Earth from the Sun? How could we observe that?



Cosmic Frontiers

Both *Voyager* spacecraft appear to have crossed the boundary region where gas expelled from the Sun encounters interstellar gas. They should be able to send signals back for 5 to 10 more years, providing measurements of the nature of interstellar space and cosmic rays outside the Solar System.

The Solar System remains the limit to our exploration of the universe with spacecraft. Most of our probes have explored only the inner part of the Solar System, although we have sent a few to explore the outer planets. The *Voyager 1* and *2* spacecraft launched in 1977 are our most distant explorers. In 1990 *Voyager 1,* having passed Pluto's orbit at more than 40 AU, looked back at the Solar System as shown in Figure 1.8. From this distance Earth was just a pale blue dot, the other planets dim points of light, and the Sun a bright star. The *Voyager 1* spacecraft is now more than four times as far from the Sun as Neptune, traveling about 3 AU farther away every year.

Even at their high speeds leaving the Solar System, the two *Voyager* spacecraft will travel for tens of thousands of years before they pass close to any other stars. Our ability to explore the universe is not, however, limited to direct study with spacecraft. With telescopes and an understanding of astrophysics, our view extends far beyond the Solar System to reveal that there are planets orbiting other stars, and there are billions of other stars with much to teach us about our own star.

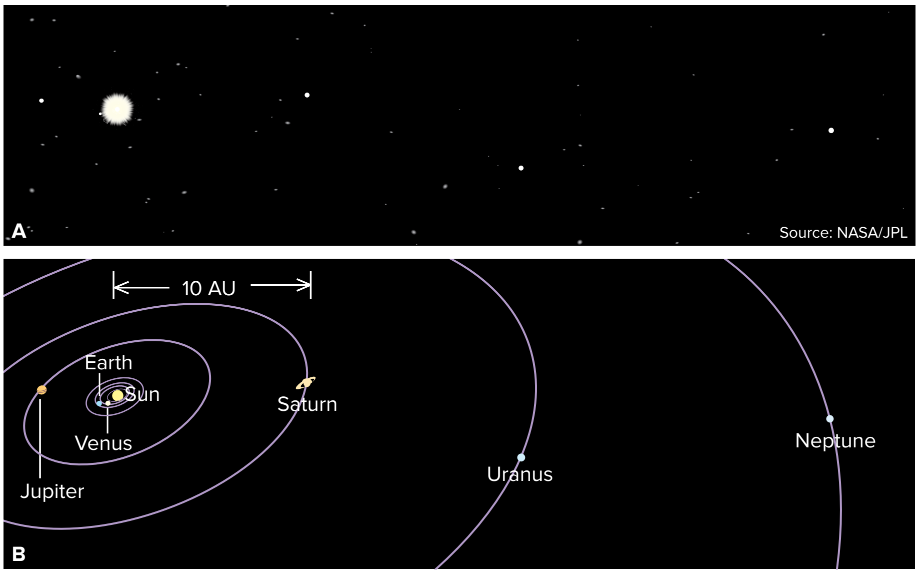


FIGURE 1.8 (A) This view of the Solar System is based on a set of images made by the *Voyager 1* spacecraft when it was about 40 AU from the Sun and about 20 AU above Neptune's orbit. The images of the planets (mere dots because of their immense distance) and the Sun have been made bigger and brighter in this view for clarity. Mercury is lost in the Sun's glare, as is Mars, which happened to lie nearly in front of the Sun at the time the image was made. (B) The planets' positions along their orbits are illustrated on the date the image was made in February 1990. Notice the immense, empty spaces between the planets and the nearly concentric rings of the planets' orbits, which make a nearly flat system.

KEY POINTS

- Earth is one planet in the Solar System, which contains the Sun, eight planets, and a huge number of smaller objects.
- The planets vary tremendously in size and appearance, some much larger than Earth and some smaller.
- The Sun is the largest body by far in the Solar System, and the energy it radiates warms the surfaces of the planets.
- Astronomers generally use the metric system for measurements, but they also use the size or mass of familiar objects like Earth as a unit to describe other bodies.
- The spaces between bodies in the Solar System are enormous compared to their sizes, so astronomers use the distance between the Sun and Earth (the "astronomical unit") to measure distances in the Solar System.

KEY TERMS

astronomical unit (AU), 6
metric system, 2
planet, 1
satellite, 2
Solar System, 5
star, 4
unit, 6

CONCEPT QUESTIONS

Concept Questions on the following topics are located in the margins. They invite thinking and discussion beyond the text.

1. The Moon's appearance and perception of the heavens (p. 3)
2. Sources of internal heat in the Sun and planets (p. 4)
3. Effect on Earth of varying distance from the Sun (p. 6)

REVIEW QUESTIONS

4. What are the eight planets in order of distance from the Sun?
5. What is a dwarf planet? Can you name two objects currently in this category?
6. Which planets are most similar to Earth?
7. About how many times bigger in radius is the Sun than Earth? How many times bigger in mass?
8. Besides the Sun and planets, what other kinds of objects are members of the Solar System?
9. What is an astronomical unit?

QUANTITATIVE PROBLEMS

10. If you use a volleyball as a model of Earth, how big would 1 kilometer be on it? The volleyball has a circumference of 68 cm.
11. What would be the circumference and diameter (circumference = $\pi \times$ diameter) of a ball that would represent the Moon if Earth were a volleyball? What kind of ball or object matches this size? (Note: For this and the following questions you will probably need to look up the sizes and distances of astronomical objects in the set of tables in the Appendix.)
12. If Earth were a volleyball, what would be the diameter of the Sun? What object matches this size?
13. How many astronomical units away is the Moon from Earth?
14. During the 1960s and 1970s, the *Apollo* spacecraft took humans to the Moon in three days. Traveling to Mars requires a trip of about 2 astronomical units in total. How long would this trip take, traveling at the same speed as to the Moon?
15. Using the same assumptions as in the previous question, how long would it take to travel to Pluto, about 40 astronomical units away?

TEST YOURSELF

16. Which of the following lists gives the sizes of the objects from smallest to largest?
    a. Moon, Earth, Pluto, Mars, Jupiter
    b. Pluto, Mars, Moon, Earth, Jupiter
    c. Jupiter, Pluto, Mars, Moon, Earth
    d. Moon, Mars, Jupiter, Earth, Pluto
    e. Pluto, Moon, Mars, Earth, Jupiter
17. Which of the following lists gives the distances of the objects from the Sun from smallest to largest?
    a. Ceres, Venus, Jupiter, Neptune, Eris
    b. Venus, Eris, Ceres, Neptune, Jupiter
    c. Eris, Ceres, Venus, Neptune, Jupiter
    d. Venus, Ceres, Jupiter, Neptune, Eris
    e. Ceres, Eris, Venus, Jupiter, Neptune
18. About how many times larger is Earth's diameter compared to the Moon's?
    a. 2 times c. 10 times e. 100 times
    b. 4 times d. 25 times
19. About how many times larger is the Sun's diameter compared to Earth's?
    a. 2 times c. 10 times e. 100 times
    b. 4 times d. 25 times
20. Which of the following properties is primarily responsible for the difference in the surface appearances for the Moon and Earth?
    a. Over the history of the Solar System, the Moon has been struck more often than Earth.
    b. The Moon's mass is much smaller than Earth's.
    c. Earth spins many times faster than the Moon.
    d. Living organisms are found throughout the surface of Earth while none have been found on the Moon.

PART 1

UNIT 2

Beyond the Solar System

2.1 Stellar Evolution
2.2 The Light-Year
2.3 The Milky Way Galaxy
2.4 Galaxy Clusters and Beyond
2.5 The Still-Unknown Universe

Part 1 Photo Credit: Stocktrek Images/Getty Images

Learning Objectives

Upon completing this Unit, you should be able to:

- List the range of masses of stars and describe the basic steps in their evolution.
- Describe the overall structure and content of the Milky Way.
- Explain how the light-year is calculated, and list its approximate size.
- Compare distances within and between galaxies, and describe larger structures.
- Describe the Big Bang and the "dark" components of the universe.

On a clear night you can see several thousand stars with your unaided eyes. If you are far from city lights, you may be able to see a pale band of light known as the Milky Way stretching across the sky. Astronomers use telescopes to probe much deeper. They have learned that the Sun is itself a star, just one among hundreds of billions in the Milky Way. The Milky Way is in turn just one among hundreds of billions of galaxies in the known universe.

Some stars are similar to the Sun, and observations of them give us insights into the Sun and Solar System (Unit 1). Other stars are drastically different, and astronomers deduce that in some cases this is because the stars are in different stages of their lifetimes. We give a brief preview of a few aspects of stars in this Unit, returning for a deeper examination in Part IV.

Larger objects, such as galaxies, are held together by the force of gravity (Unit 4). Gravity reaches across the empty space between objects and can link them together into gravitationally bound systems. For example, gravity is what holds the planets in orbit around the Sun to make the Solar System. Gravity is also what pulls the hundreds of billions of stars within the Milky Way into orbit around the center of our Galaxy. To provide a context for our studies, we give an overview of galaxies and even larger gravitational systems in this Unit; we examine them in greater detail in Part V of the book.

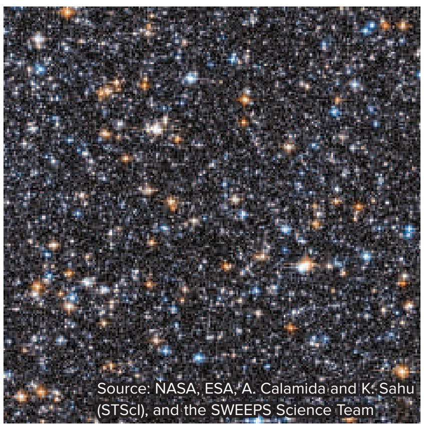


FIGURE 2.1 A deep image of a small portion of the Milky Way made with the Hubble Space Telescope. The image reveals stars too faint to be seen individually with your eyes alone. Slight differences in the colors of stars are caused by the stars' temperatures.

2.1 STELLAR EVOLUTION

The night sky is filled with myriad stars, as seen in Figure 2.1. Some stars are much like the Sun, but others are thousands of times larger or smaller. The brightest stars produce over a billion times more light than the dimmest stars. Some stars are much hotter than the Sun and shine a dazzling blue-white, whereas others are cooler and glow a pale orange or red.

The Sun and its properties provide a convenient comparison for understanding other stars. Astronomers often describe stars' masses as ranging from 0.1 to 100 "solar masses," or 0.1 to 100 $M_\odot$ (the $\odot$ symbol is the international symbol for the Sun). The mass of a star appears to be the most critical factor in determining its difference from other stars. The stronger gravity of a more massive star drives up the rate of nuclear fusion dramatically, while less massive stars consume their fuel at a more leisurely pace.

FIGURE 2.2 Hubble Space Telescope image of a cloud of gas and dust in the Milky Way. On the scale of this picture, the Solar System out to Neptune is about 1000 times smaller than the period ending this sentence.

In Part IV of this book we will see how astronomers have pieced together evidence that allows us to understand how stars are born, how they change as they age, and the dire fates they face when they run out of fuel. These changes, called **stellar evolution** by astronomers, are driven by the inexorable pull of gravity. Discovering the story of stars' lives has been one of the great triumphs of astrophysics and the scientific method during the last few centuries.

Deep images like that in Figure 2.2 reveal that stars intermingle with immense clouds of gas and dust. These are the sites of stellar birth. Within cold, dark clouds, gravity may draw the gas into dense clumps that collapse to form new stars, heating the gas around them until it glows. Stars eventually burn themselves out, but they do not go quietly. Stars like the Sun shine for billions of years until their final phases, when they tear themselves apart before fading away. The most massive stars die after just a few million years in titanic explosions, spraying radioactive matter outward to mix with the vast clouds of gas lying between the stars. This matter from exploded stars is ultimately recycled into new stars.

Making sense of the story of how stars are born and die has led to a greatly expanded vision of the kinds of objects that exist in the universe. We now know of remarkable objects that are beyond anything imagined a century ago. There are huge numbers of "failed" stars—objects that weren't quite massive enough to start the fusion of hydrogen to helium of the stars that shine in the night sky. And when stars die, they leave behind bizarre corpses—huge amounts of matter compacted into tiny objects such as white dwarfs, neutron stars, and black holes.

The life stories we have deduced from studying other stars tell us that when the Sun runs out of hydrogen fuel in 5 or 6 billion years, it will undergo drastic changes as it restructures itself to use helium fuel instead. We can predict that the Sun will go through a phase in which it will expand and nearly swallow up Earth. The enormous energy output during this phase will heat the rock in our planet until it is entirely molten. The Sun will end this luminous phase by blowing away its own atmosphere, and the remaining hot, dense core—a white dwarf—will slowly fade like a cooling ember after a campfire has burned out.

2.2 THE LIGHT-YEAR

While the "astronomical unit" (AU) works well for describing distances in our Solar System, distances between stars are so immense that the AU is inappropriately small. The second-nearest star (after the Sun!) is hundreds of thousands of AU away. A convenient way of describing such distances is the "light-year."

Measuring a distance with a unit that refers to time may at first sound peculiar, but we do it all the time in everyday life. For example, we might say that our town is a two-hour drive from the city, or our dorm is a five-minute walk from the library. In making such statements, we imply that we are traveling at a standard speed: freeway driving speed or a walking pace.

Astronomers have a superb speed standard: the speed of light in empty space. This is a constant of nature equal to 299,792,458 meters per second. We usually round this off to 300,000 kilometers per second (about 186,000 miles per second). Moving at this constant, universal speed, light in one year travels a distance defined

Mathematical Insight

To calculate the length of a light-year from light's speed in kilometers per second, you need to first find the number of seconds in a year. You can do this by multiplying the number of days in a year times the number of hours in a day times the number of minutes in an hour times the number of seconds in a minute.

to be 1 **light-year,** abbreviated as 1 ly. This works out to be about 10 trillion kilometers (6 trillion miles). Although we achieve a major convenience in adopting such a huge distance for our scale unit, we should not lose sight of how truly immense such distances are. For example, if we were to count off the kilometers in a light-year, one every second, it would take us more than 300,000 years!

The star nearest our Sun is 4.2 light-years away. As we gaze deeper into space, we find that stars are typically separated by a few light-years in the Sun's neighborhood, but in some places the stars are concentrated much closer together, just a fraction of a light-year separating them. As we look out even farther, tens of thousands of light-years away, the stars eventually taper off, marking the outskirts of the vast system of stars to which our star belongs.

2.3 THE MILKY WAY GALAXY

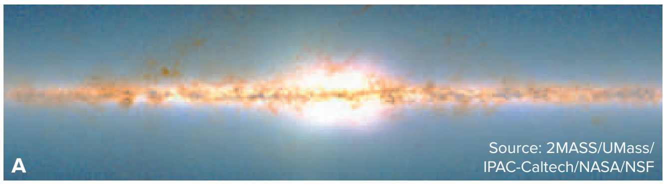
Our Sun and the stars we see at night are part of an immense system of stars called the **Milky Way Galaxy**: a collection of several hundred billion stars, along with billions of solar masses of gas and dust. Our Galaxy has a flattened disklike shape somewhat like the shape of the Solar System (Figure 2.3), but with a diameter roughly 100 million times larger. The center of the Milky Way looks bright because stars are more crowded together than they are out at the Sun's orbit. Nevertheless, the stars are still separated by huge distances and almost never collide. The Sun and other stars orbit around the center, but it takes the Sun several hundred million years to complete one trip around this immense disk.

Concept Question 1

In what ways are the Solar System and Milky Way similar and different?

We can use the light-year for setting the scale of the Milky Way Galaxy. In light-years, the visible disk is more than 100,000 light-years across, with the Sun orbiting roughly 25,000 light-years from the center. Throughout the disk of the Milky Way are scattered gas clouds with sizes of up to hundreds of light-years across. Some of these clouds contain more than a million times the Sun's mass, but they are so diffuse that their overall density is less than a billionth-trillionth of the density of the air we breathe.

In this huge swarm of stars and clouds, the Solar System is all but lost—like a single grain of sand on a vast beach—forcing us again to grapple with the problem of scale. Stars are almost unimaginably remote: Even the nearest one to the Sun is about 40 trillion kilometers (25 trillion miles) away—about 10,000 times farther than Neptune. Such distances are so immense that analogy is often the only way to grasp them. For example, if we think of the Sun as a pinhead, the nearest star would be another pinhead about 60 kilometers (35 miles) away, and the space between them would be nearly empty. On this scale, the Sun is to the size of the Milky Way as a pinhead is to the size of the Sun itself.



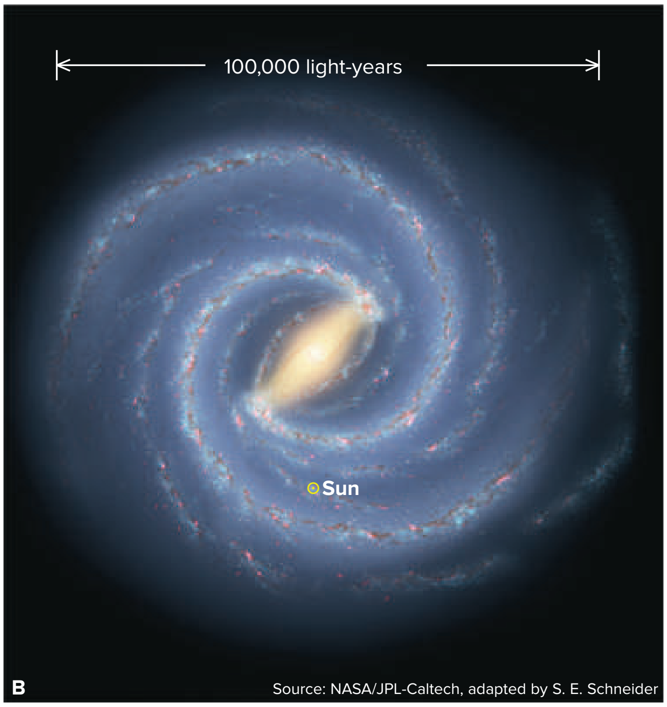
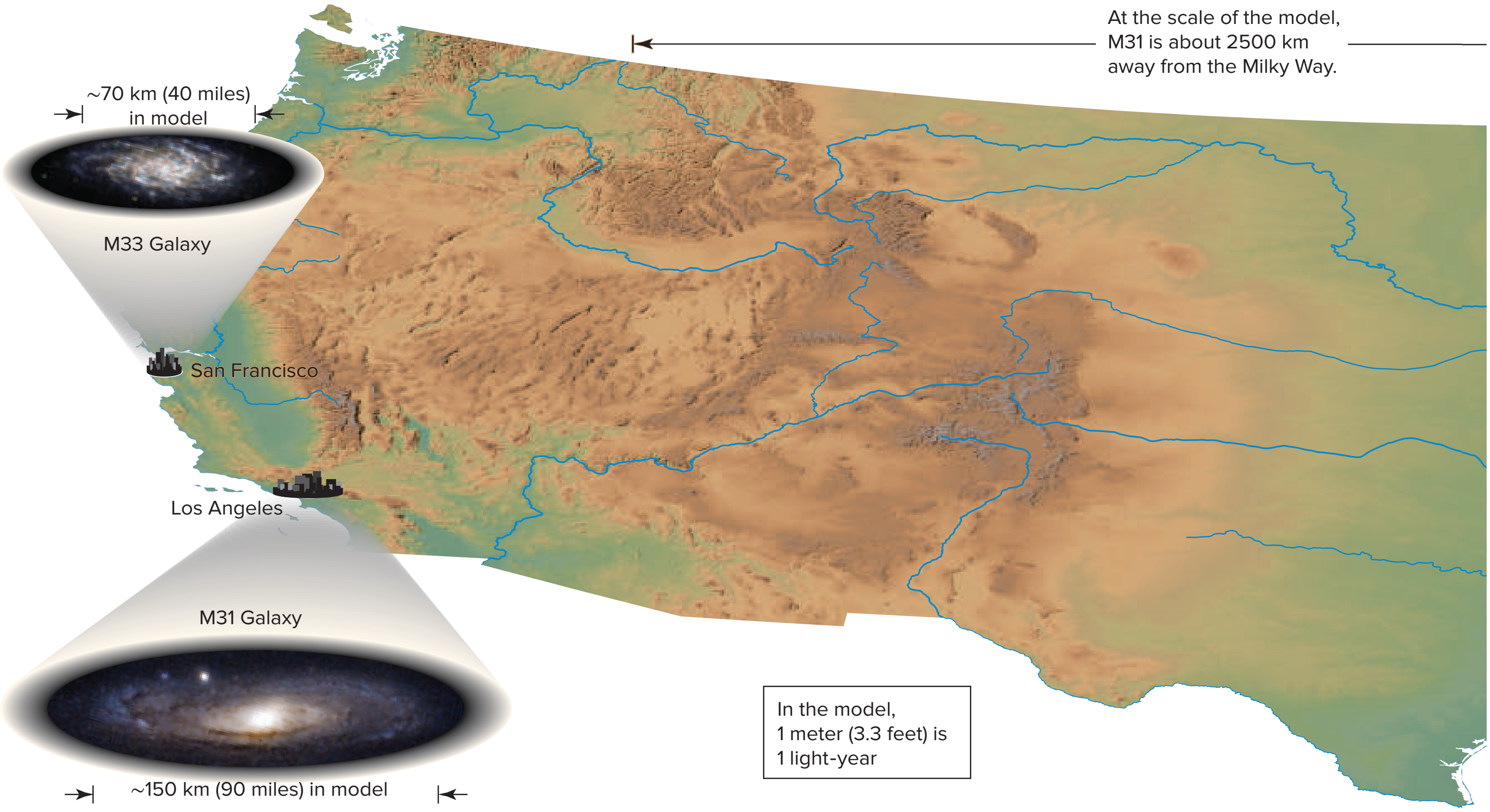


FIGURE 2.3 The Milky Way Galaxy. (A) The view from our position within the disk of the Galaxy made by plotting stars in the 2MASS star catalog. The brown-colored areas running horizontally across the image are caused by dust clouds that partially block the light from background stars. (B) The approximate structure of the Milky Way if it were seen from above, as mapped out by the Spitzer Space Telescope.



(M33 Galaxy) NASA/JPL-Caltech, adapted by S. E. Schneider, (M31 Galaxy) Buras/Shutterstock, adapted by S. E. Schneider, (Milky Way) NASA Jet Propulsion Laboratory (NASA-JPL), adapted by S. E. Schneider

FIGURE 2.4 An approximate scale model of the Local Group in which 1 meter represents 1 light-year. At this scale the three largest galaxies in the Local Group are roughly as far from each other as Los Angeles, Chicago, and San Francisco, cities that, with their surrounding suburbs, are roughly the correct relative size of these galaxies. The Solar System's planets orbit within an area smaller than a pinhead on this scale.

LOOKING UP #3

M31 is visible to the naked eye in the constellation Andromeda.

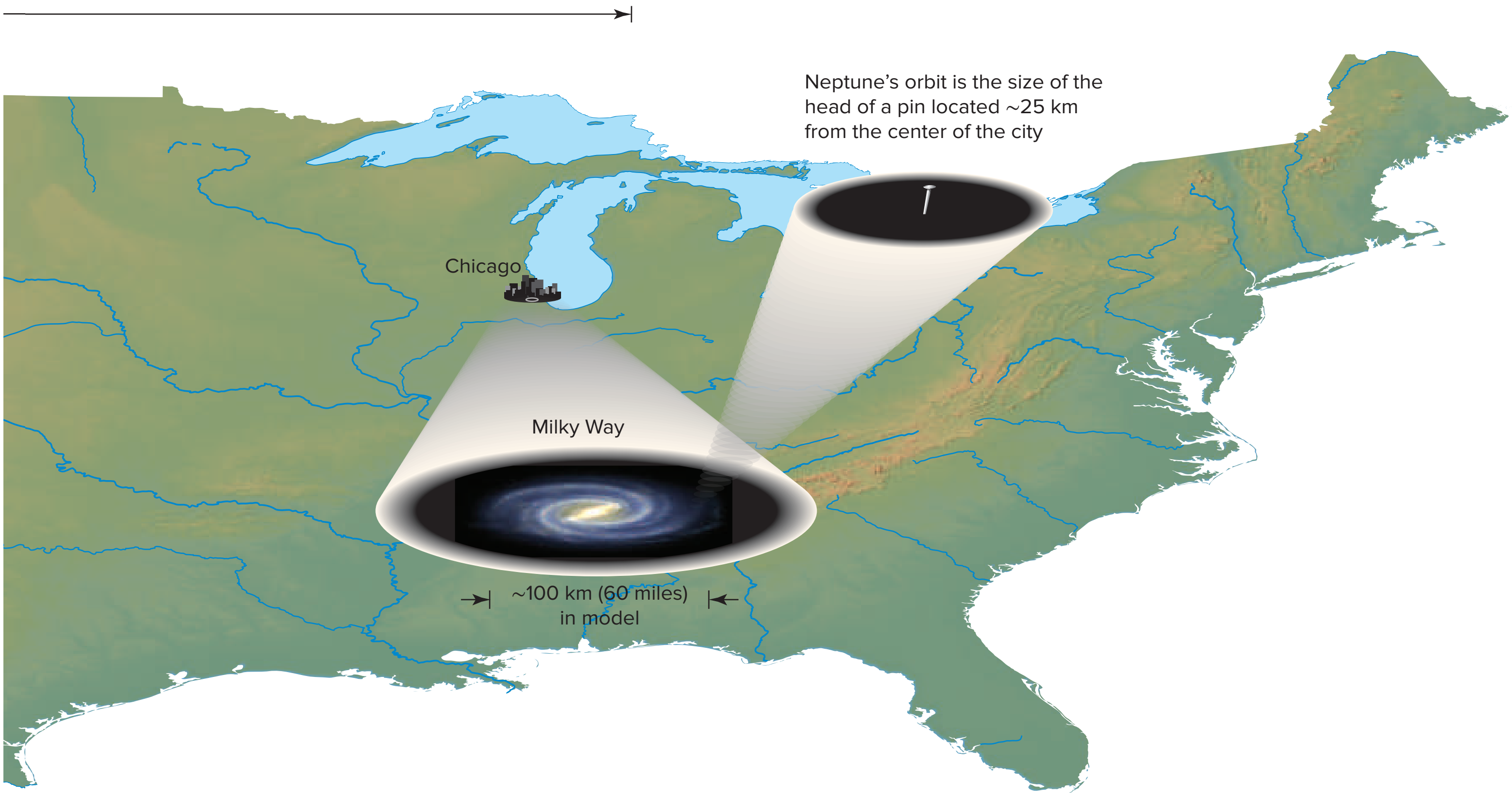
2.4 GALAXY CLUSTERS AND BEYOND

Having gained some sense of scale for the Milky Way, we now resume our exploration of the cosmic landscape, pushing out to the realm of other **galaxies** like the Milky Way, each an enormous island of stars, gas, and other matter. Here we find that just as stars are gravitationally bound into star clusters and galaxies, so galaxies are themselves bound into **galaxy groups** and **galaxy clusters.**

The Milky Way is part of a collection of galaxies called the **Local Group.** It is "local" because it is the one we inhabit. The Local Group is a relatively small concentration of galaxies, containing only about four dozen galaxies, but it is still about 3 million light-years in diameter. The Milky Way is the second-largest galaxy in the Local Group after the Andromeda Galaxy, also known as M31, the catalog number of a galaxy about 2.5 million light-years away from us.

To gain some perspective on the size of the Milky Way and Local Group, imagine that we built a model in which a light-year was scaled down to just 1 meter. At this scale Neptune's orbit would fit inside the head of a pin, and the Sun would be the size of a virus. The Milky Way Galaxy would be the size of a large city—about 100 kilometers (60 miles) across, while M31 would be another city about 2500 kilometers away (Figure 2.4). Given the enormous scale of this model, light crawls along about as fast as a plant might grow—just a meter per year; so that even at light speed, a trip from the Milky Way to M31 would take 2.5 million years!

The Milky Way is currently moving at about 90 kilometers per second (about 300,000 kilometers per hour, or 200,000 miles per hour) toward M31. Originally these two galaxies were moving away from each other, but the gravitational pull between them caused them to slow down, stop, and ultimately fall back toward



each other. In about 5 billion years the Milky Way and M31 will crash into each other, and the stars and gas in the Milky Way's disk will be flung into wild new orbits, probably sending our Solar System flying off into intergalactic space.

FIGURE 2.5 Photograph of the central region of the Virgo Cluster. The Milky Way and the entire Local Group have been slowed in their motion away from this galaxy cluster by its strong gravitational pull.

We have to adjust the scale of our thinking again to imagine even larger scales. The Local Group is one of dozens of galaxy groups surrounding a much larger assemblage of galaxies called the **Virgo Cluster,** like suburbs surrounding a major city. The Virgo Cluster is centered about 50 million light-years away and itself contains thousands of galaxies. The central region of the Virgo Cluster is shown in Figure 2.5.

The term *Virgo Supercluster* has sometimes been used to describe the enormous "metropolitan area" of the Virgo Cluster with its surrounding galaxy groups, but this collection of groups and clusters is just a modest example of an even larger scale of clustering. The term **supercluster** is now generally reserved for collections of many galaxy clusters (and their associated surrounding regions), gravitationally bound to one another in structures that span hundreds of millions of light-years.

The mind boggles at these enormous gravitational structures, and perhaps you have begun to wonder whether this hierarchy of structures extends ever upward. But structures of such vast size are about as large as we can see before taking the final jump in scale to the **universe** itself. Although for centuries our knowledge of the visible universe was confined by the limits of our telescopes and instruments, today we are reaching a fundamental limit: We can see only as far away as light has had time to travel in the age of the universe.

TABLE 2.1 Scales of the Universe

Object	Approximate Radius
Earth	6400 km (4000 miles) = $R_{\oplus}$
Moon's orbit	380,000 km ≈ 60 × $R_{\oplus}$
Sun	700,000 km = $R_{\odot}$ ≈ 109 × $R_{\oplus}$
Earth's orbit	150 million km = 1 AU ≈ 214 × $R_{\odot}$
Solar System to Neptune	4.5 billion km ≈ 30 AU
Nearest star	270,000 AU ≈ 4.2 light-years (ly)
Milky Way Galaxy	50,000 ly
Local Group	1.5 million ly
Local Supercluster	50 million ly
Visible universe	13.8 billion ly

Concept Question 2

Suppose we extended the scale model in Figure 2.4. How far away would the Virgo Cluster be? How large would the observable universe (out to 13.8 billion light-years) be?

The best evidence today indicates that the universe is 13.8 billion years old, and therefore we cannot see any farther than light can have traveled in that time. The largest superclusters we see span nearly 1% of the visible universe, but as best we can determine, the universe is relatively uniform over larger spans than this.

Within the 13.8 billion light-years we can see, there is no hint of an edge or change in the nature of the universe. This suggests that the universe must be far larger than what we can see. Current ideas of how the universe began predict that the universe is immensely larger, perhaps extending limitlessly. Regardless of our uncertainty about the known universe's overall size, we can observe that it has a well-ordered hierarchy of smaller structures. Small objects are clustered into larger systems, which are themselves clustered: satellites around planets, planets around stars, stars in galaxies, galaxies in clusters, clusters in superclusters, as shown in Table 2.1 and illustrated in Figure 2.6. This set of structures originated as a result of the pull of gravity and the ways in which matter interacts on different scales.

2.5 THE STILL-UNKNOWN UNIVERSE

Over the last century, astronomers have uncovered evidence that the entire universe behaves in ways that were utterly unexpected a hundred years ago. Measurements show that galaxies are flying away from each other in what looks like a vast explosion, called the **Big Bang.** However, Albert Einstein's general theory of relativity showed that this is the wrong way to interpret these motions. Instead, space itself is expanding, carrying the galaxies along with it. Einstein's theories (Units 26 and 27), now cornerstones of modern physics, have forced us to reevaluate our most basic notions of space and time. Moreover, we are discovering that there is much more to the universe than we can directly see through our telescopes.

Far more matter is found to fill the universe than what we can see in planets, stars, gas clouds, galaxies, and so on. To explain the inexplicably strong gravitational pull of galaxies, there must be about five times more utterly invisible **dark matter** present. The evidence that dark matter exists comes from a variety of sources. The motions of stars in the outer parts of galaxies are so fast that they would fly off into intergalactic space unless much more mass is present than we can see. The same has been found true for the orbits of galaxies in galaxy clusters. Observations of gas in the earliest stages of the universe also provide evidence of dark matter, and they indicate that it is made of strange substances that cannot form stars or planets. This is the subject of intense ongoing investigations, and it may be that particle

Concept Question 3

The idea of dark matter may seem quite unusual, but can you think of any situations in which you have been able to find evidence that something was present without actually seeing it? Were you later proved correct?

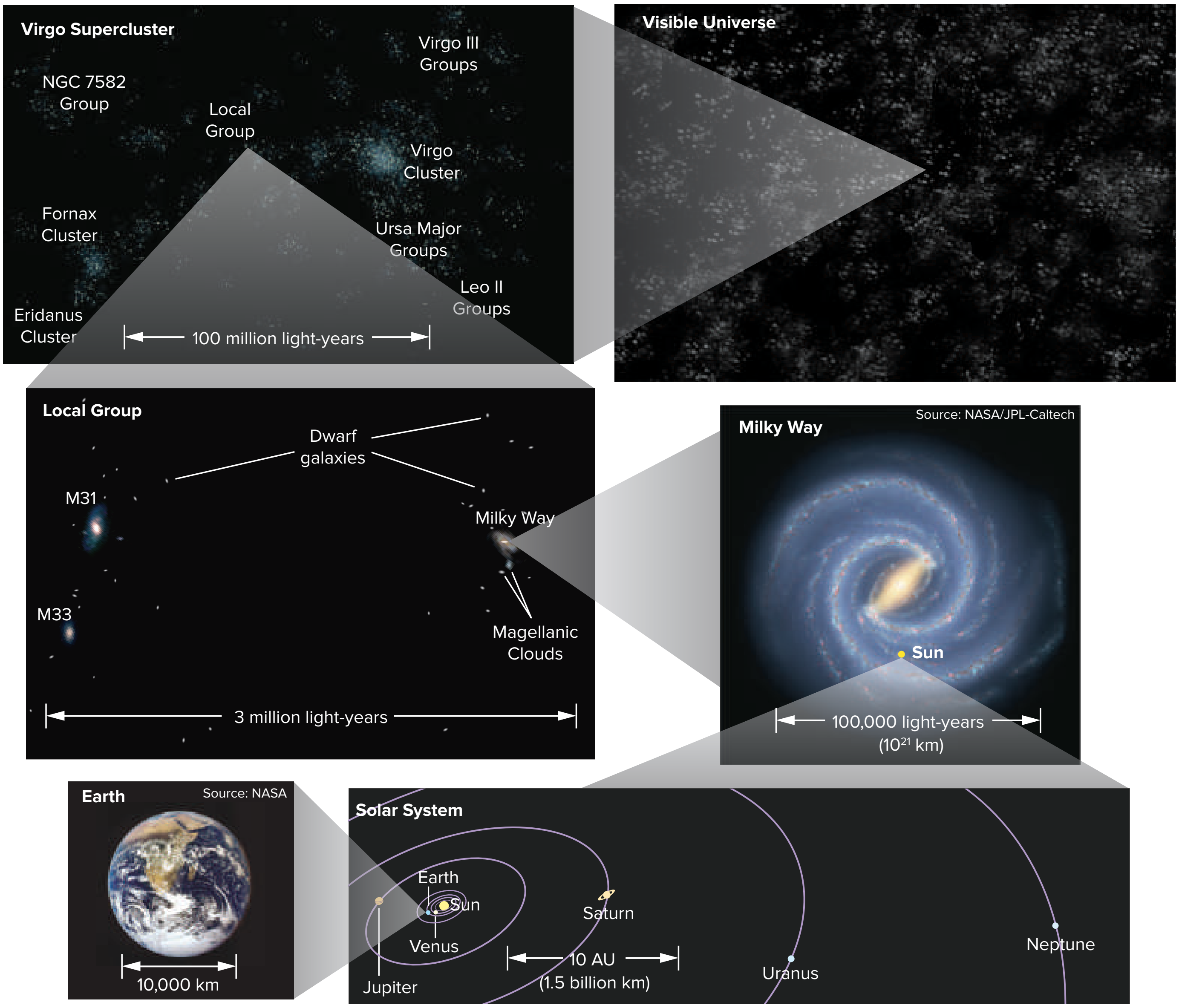


FIGURE 2.6 Earth is but one of eight planets orbiting our star, the Sun. The Sun is but one of hundreds of billions of stars in our Galaxy, the Milky Way. The Milky Way is the second largest among dozens of galaxies in our "Local Group." The Local Group is one of the smaller "clusters" of galaxies that make up the "Virgo Supercluster." The universe is filled with millions of other superclusters stretching to the limits of our vision.

physicists, exploring the submicroscopic world at scales far smaller than atoms, will uncover the nature of this strange kind of matter.

Over the last decade, astronomers have also accumulated evidence for an even stranger substance that has been dubbed **dark energy.** This is an energy that pervades every corner of space—even the emptiest vacuum. Einstein predicted the possibility of such an all-pervasive energy, but based on the evidence of his day, he abandoned the idea. New evidence suggests that not only does dark energy exist, it "outweighs" all of the visible and dark matter in the universe. If the latest measurements are correct, dark energy will drive the expansion of the universe faster and faster, perhaps in the extremely remote future causing space to expand so rapidly that it will tear apart the visible universe!

Cosmic Frontiers

The Dark Energy Spectroscopic Instrument (DESI) survey scheduled to begin in 2019 is one of several new experiments that will provide much greater detail about how dark energy may be affecting the expansion of the universe.

KEY POINTS

- The Sun is a fairly typical star, and we can learn about its past and future by studying other stars.
- Stars have a range of masses, and the more massive stars are brighter and have shorter lifetimes.
- The Sun will last about 10 billion years, and it is just one among hundreds of billions of stars that make up the Milky Way Galaxy.
- Other galaxies are seen out to the most remote visible regions, often found in "clusters" or "superclusters."
- Astronomers often use the "light-year," the distance light travels in a year, to describe interstellar and intergalactic distances.
- The nearest star is 4.2 light-years away from the Sun. Other galaxies are millions to billions of light-years distant.
- The universe began with a "Big Bang" in which space began expanding at high speeds.
- Structures such as galaxies and clusters are held together by gravity, but there is evidence of much more matter in these structures than can be directly seen, which astronomers call "dark matter."
- The way the universe is expanding suggests that "dark energy" fills it and "weighs" more than all the matter.

KEY TERMS

Big Bang, 14
dark energy, 15
dark matter, 14
galaxy, 12
galaxy cluster, 12
galaxy group, 12
light-year, 11
Local Group, 12
Milky Way Galaxy, 11
stellar evolution, 10
supercluster, 13
universe, 13
Virgo Cluster, 13

CONCEPT QUESTIONS

Concept Questions on the following topics are located in the margins. They invite thinking and discussion beyond the text.

1. Comparing the Solar System and Milky Way (p. 11)
2. Making a scale model of the universe (p. 14)
3. Detecting what you cannot see (p. 14)

REVIEW QUESTIONS

4. What do astronomers mean by stellar "evolution"?
5. What is a galaxy?
6. Roughly how big across is the Milky Way Galaxy?
7. How is a light-year defined?
8. To what systems (in increasing order of size) does Earth belong?
9. What do the terms *dark matter* and *dark energy* refer to?

QUANTITATIVE PROBLEMS

10. If the Milky Way were the size of a nickel (about 2 centimeters in diameter): (a) How big would the Local Group be? (b) How big would the Local Supercluster be? (c) How big would the visible universe be? (The data in Table 2.1 may help you here.)
11. If we detected radio signals (which travel at the speed of light) of intelligent origin from the Andromeda Galaxy (M31) and immediately responded with a radio message of our own, how long would we have to wait for a reply?
12. How long does it take light to travel from the Sun to Earth?
13. If the Milky Way is moving away from the Virgo Cluster at 1000 kilometers per second, how long does it take for the distance between them to increase by 1 light-year?
14. The Milky Way is moving toward the larger galaxy M31 at about 100 kilometers per second. M31 is about 2.5 million light-years away. How long will it take before the Milky Way collides with M31 if it continues at this speed?
15. Some distant galaxies seen by the Hubble Space Telescope are 12 billion light-years away. Using the scale in Figure 2.4 (where the Milky Way is about the size of a large city), how far would that be in the model?

TEST YOURSELF

16. Which of the following is the best analogy? Earth is to the Solar System as
    a. the Sun is to the Local Group.
    b. the Local Group is to the visible universe.
    c. the Sun is to the Milky Way.
    d. the Local Group is to the Milky Way.
    e. the Virgo Cluster is to the Local Group.
17. Which of the following astronomical systems is/are held together by gravity?
    a. The Sun c. The Milky Way e. All of them
    b. The Solar System d. The Local Group
18. The light-year is a unit of
    a. time. b. distance. c. speed. d. age. e. all of these.
19. Rank the following systems from smallest to largest in size.
    a. Milky Way, Local Group, Virgo Cluster, Solar System
    b. Solar System, Local Group, Milky Way, Virgo Cluster
    c. Virgo Cluster, Local Group, Milky Way, Solar System
    d. Solar System, Milky Way, Local Group, Virgo Cluster
    e. Local Group, Solar System, Milky Way, Virgo Cluster
20. The Sun orbits the center of the Milky Way at a much higher speed than would be expected based on the mass of visible stars. What do astronomers think probably explains this discrepancy?
    a. Large numbers of unseen planets
    b. A large number of undetected black holes
    c. Dark matter
    d. Dark energy
    e. An unobserved object that is gravitationally attracting the Sun

PART 1

UNIT 3

Astronomical Numbers

3.1 The Metric System
3.2 Scientific Notation
3.3 Special Units
3.4 Approximation

Part 1 Photo Credit: Stocktrek Images/Getty Images

Learning Objectives

Upon completing this Unit, you should be able to:

- Understand the meaning of exponential notation, and carry out calculations with exponential notation in multiplication and division.
- Identify the powers of 10 associated with commonly used metric prefixes.
- Describe the basic units in the MKS system and relate them to English system units.
- Convert a number into and out of scientific notation, and describe the purpose of this notation.
- Explain why astronomers use some nonmetric units, and carry out a calculation to convert between different units.
- Define significant digits, and describe how results should be rounded off when carrying out calculations.

Astronomy deals with a greater range of numbers than any other science. It is challenging to grasp, even figuratively, the vast range of the measurements needed to study the universe (Figure 3.1). To understand a planet that has a diameter of 13,000,000 meters, we also need to understand the interactions between atoms that are only 0.0000000001 meter in diameter. And as we discuss other aspects of the universe, we will be considering sizes, masses, brightness, energy, and times that span even greater ranges.

To deal with this vast array of numbers, astronomers use four different strategies: (1) the metric system, (2) scientific notation, (3) special units, and (4) approximation. We will look at each of these approaches in turn, but we can summarize these procedures briefly as follows.

The *metric system,* as opposed to the English system, allows easy conversions between larger and smaller **units** of measure, such as between meters and kilometers. To carry out many calculations, we must express measurements in fundamental units such as meters, seconds, and kilograms. Faced with numbers like 13,000,000 and 0.0000000001, astronomers use a way of abbreviating these numbers called *scientific notation.* This notation keeps track of the order of magnitude of a number separately from its precise value.

Metric units do not always prove convenient for interpreting the sizes of things, so sometimes we create special units with a clear physical meaning, such as the astronomical unit (Unit 1.6) or the light-year (Unit 2.2). Often the essential information we need about a number is just its approximate size, so astronomers round off values. This avoids focusing on a level of precision that is not important. We say, for example, that the astronomical unit, which stands for Earth's distance from the Sun, is 150 million kilometers even though it is known to be 149,597,870 kilometers.

This mathematical background is important for understanding much of the material in astronomy, but it does not necessarily have to be mastered all at once. Return to this Unit whenever the numbers seem overwhelming.

Source: Library of Congress [48031341]

FIGURE 3.1 The "Ancient of Days" taking the measure of the universe. Etching by William Blake (ca. 1794).

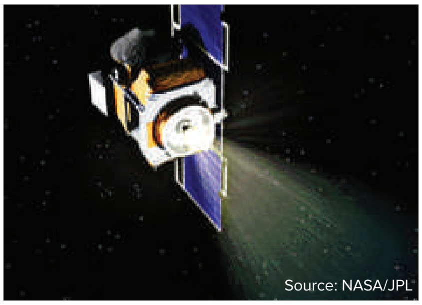


FIGURE 3.2 The *Mars Climate Orbiter* crashed due to confusion between English and metric units.

It is often forgotten today that the English system also offers many intermediate size scales, but their relationships are complex. The inch is divided into 12 "lines," the foot into 12 inches, the yard into 3 feet, the "rod" into 5.5 yards, the "chain" into 4 rods, the "furlong" into 10 chains, the mile into 8 furlongs, and the "league" into 3 miles. The acre, still commonly used as a measure of area, is 1 furlong long by 1 chain wide. As if this is not enough to give one a headache, weights and volumes were divided in completely different ways!

Mathematical Insight

The trick to converting from one unit to another is to multiply by "1." *One* can be written in many ways. If a and b are equal, then $\frac{a}{b} = 1$. In the conversion of kilometers to meters, because $1\text{ km} = 10^3\text{ m}$, we multiply by $\frac{10^3\text{ m}}{1\text{ km}}$. This lets us cancel out the kilometer units because they appear in both the numerator and the denominator.

3.1 THE METRIC SYSTEM

Before the metric system was introduced in 1791, widely varying systems of measurement were used in different countries, or even in different regions within a single country. For example, the Paris foot was 6.63% longer than the English foot, while the Spanish *vara* was 8.67% shorter than the English yard. Similarly, the French pound (*livre*) was 10.2% larger than the English pound, and many other weight measures were in common use even just within Europe. Confusion about measurements was widespread and required frequent conversion between different units.

That same confusion caused the loss of the *Mars Climate Orbiter* spacecraft (Figure 3.2) in 1999. The company building navigation jets provided its thrust data in English units, but NASA mission controllers thought the units were metric. Firing the thrusters caused the craft to go off course and crash. Today the metric system has been widely adopted; the complex system of English units is still the primary choice only in the United States, Liberia, and Myanmar. The units used are not essential for appreciating the important ideas of astronomy, but it is helpful to be familiar with the metric system for the calculations we will carry out.

The great advantage of the **metric system** over the English system is that different units are related by factors of 10, making it much simpler to convert from one unit to another—1 kilometer is 1000 meters, whereas 1 mile is 5280 feet. We can usually convert between metric units by just "moving the decimal point" instead of multiplying or dividing by a conversion factor like 5280 feet per mile.

Each time we move the decimal point, we are performing the equivalent of multiplying or dividing by factors of 10. Mathematically, we can use **exponents** to indicate the *number* of times we multiply by 10. An exponent indicates how many times we multiply a quantity by itself. For example, there are 1000 meters in a kilometer. We can write 1000 as "10 to the third power" or "10 to the exponent 3" as follows:

$$1000 = 10 \times 10 \times 10 = 10^3.$$

When we convert meters to kilometers, we also move the decimal point over three places:

$$1\text{ km} = 1.\text{ km} \times \frac{10^3\text{ m}}{1\text{ km}} = 1000.\text{ m},$$

where we have used the abbreviations m for meters and km for kilometers, and we have explicitly included the decimal point for clarity.

When a number is multiplied by 10^3, we move the decimal point to the right by 3 places. When divided by 10^3, we move the decimal point to the *left* by 3 places. This second case can also be written as multiplying by 10^{-3}. In other words "10 to the power negative 3" is the equivalent of one thousandth (1/1000). When we take 10 (or any number) to the "zeroth power," the result is always one: $10^0 = 1$.

Similarly, we can write 1 billion as

$$1{,}000{,}000{,}000. = 10 \times 10 \times 10 \times 10 \times 10 \times 10 \times 10 \times 10 \times 10 = 10^9,$$

or one millionth as

$$0.000001 = \frac{1}{1{,}000{,}000.} = \frac{1}{10 \times 10 \times 10 \times 10 \times 10 \times 10} = \frac{1}{10^6} = 10^{-6}.$$

In essence, rather than writing out all the zeros, we use the exponent to tell us the number of zeros and whether the number is in the numerator or denominator.

In the metric system, **metric prefixes** identify various possible **powers of 10.** The prefix *kilo-,* for example, indicates 1000, while *milli-* indicates one thousandth, and *mega-* indicates 1 million. These prefixes can be added to any unit of measure to create a new unit that is closer to sizes we are interested in discussing: millimeter, kilogram, or megaton, for example.

TABLE 3.1 Metric Prefixes

Power of Ten	Exponential Notation	Metric Prefix	Abbre-viation
septillion	10^{24}	yotta	Y
sextillion	10^{21}	zetta	Z
quintillion	10^{18}	exa	E
quadrillion	10^{15}	peta	P
trillion	10^{12}	tera	T
billion	$\mathbf{10^{9}}$	**giga**	**G**
million	$\mathbf{10^{6}}$	**mega**	**M**
thousand	$\mathbf{10^{3}}$	**kilo**	**k**
hundred	10^{2}	hecto	h
ten	10^{1}	deca	da
tenth	10^{-1}	deci	d
hundredth	$\mathbf{10^{-2}}$	**centi**	**c**
thousandth	$\mathbf{10^{-3}}$	**milli**	**m**
millionth	$\mathbf{10^{-6}}$	**micro**	**μ**
billionth	$\mathbf{10^{-9}}$	**nano**	**n**
trillionth	10^{-12}	pico	p
quadrillionth	10^{-15}	femto	f
quintillionth	10^{-18}	atto	a
sextillionth	10^{-21}	zepto	z
septillionth	10^{-24}	yocto	y

Omikron/Science Source

FIGURE 3.3 One of the kilogram standards kept at the U.S. National Bureau of Standards. This platinum-iridium cylinder is stored under vacuum to reduce chemical reactions that might change its mass.

Mathematical Insight

The conversion here is accomplished first by converting kilowatts to watts, multiplying by $1 = \frac{1000\text{ W}}{1\text{ kW}}$, and then converting units by once again multiplying by $1 = \frac{0.00134\text{ horsepower}}{1\text{ W}}$.

TABLE 3.2 MKS Units

Quantity	Metric Unit	MKS Equivalent	English Equivalent
Length	meter	m	3.28 feet
Mass	kilogram	kg	2.2 pounds (of mass)
Time	second	sec	(same)
Area	square meter	m^2	10.76 square feet
Volume	liter (L)	10^{-3} m^3	1.06 U.S. quarts
Speed	meters per second	m/sec	2.24 miles per hour
Acceleration	meters per square second	m/sec^2	3.28 feet per square second
Density	kilograms per liter	10^3 kg/m^3	0.036 pounds per cubic inch
Force	newton (N)	$kg \cdot m/sec^2$	0.225 pounds (of force)
Energy	joule (J)	$kg \cdot m^2/sec^2$	0.000948 BTUs
Power	watt (W)	$kg \cdot m^2/sec^3$	0.00134 horsepower

Table 3.1 shows the standard metric prefixes along with their meanings in words and exponential notation. This is a complete listing of metric prefixes; in this book we use only the seven shown in boldface in the table. A nanometer, for example, is a unit we will use when discussing light waves. It is a billionth of a meter, or 10^{-9} m, and can be abbreviated nm. To convert 5 nanometers to meters, we would move the decimal point to the left by 9 places: 5. nm = 0.000000005 m. Thus, starting from a fundamental unit of measure like the meter, the metric prefixes give us a wide range of units that are appropriate in different contexts.

Any system of physical measurements requires three fundamental units—those describing length, mass, and time. In the metric system these are the meter (which is about 10% longer than the yard), the kilogram (which is about 2.2 pounds), and the second. This set of units defines the **MKS system,** which stands for meter, kilogram, and second. Units for measuring other quantities, such as force, energy, and power, can all be written in terms of these fundamental units. Some of the more common kinds of metric units we use in this book, and their nearest equivalent in the English system, are listed in Table 3.2.

One unit we use, the liter, is a unit of volume, and is not quite as simple a combination of MKS units as the others. The liter is one thousandth of a cubic meter. The liter was the basis for the original definition of the kilogram—the mass of one liter of water—but because this was not very precise, this was changed to the mass of a carefully preserved platinum cylinder (Figure 3.3), then in 2019 it was redefined in terms of fundamental physical constants that can be measured in a lab.

We will often be examining the **density** (mass per volume) of an object to try to understand its composition. For example, a planet with a density of 1 kilogram per liter has the density of water and is probably composed of ice, but one with a higher density must contain denser substances such as rock or iron. We will find places such as the centers of dying stars where the density is enormously larger, and regions of interstellar space where the density is a minuscule fraction of this.

The units in Table 3.2 can all employ metric prefixes, so the specifications for a car's power likely would be listed as, say, 200 kilowatts. To convert this to the English unit of horsepower, we could carry out the following calculation:

$$200\text{ kW} = 200{,}000\text{ W} \times 0.00134\text{ horsepower/W} = 268\text{ horsepower.}$$

Also be aware that in the English system, the term *pound* is used interchangeably for a mass (a measure of the amount of matter) as well as for the gravitational force with which Earth pulls on that mass (see Unit 14.1 for details). As we will discover, the same mass weighs a different amount on different planets.

3.2 SCIENTIFIC NOTATION

When we make a calculation in scientific notation, we usually begin by converting all of the values into MKS units. For example, the mass of the Sun is 1,989,000,000,000,000,000,000,000,000,000 kilograms. There is no metric prefix close to the size of such an enormous number, so we use a more concise way to express such numbers called *scientific notation.*

Scientific notation combines the powers-of-10 notation just described with the particular value of the number. We divide the number into a value between 1 and 10 and a power of 10 that when multiplied together yield the original number. Thus, we can write 600 (six hundred) as

$$600 = 6 \times 10 \times 10 = 6 \times 10^2.$$

We write 543,000 (five hundred forty-three thousand) as

$$543{,}000 = 5.43 \times 10 \times 10 \times 10 \times 10 \times 10 = 5.43 \times 10^5.$$

and 21 millionths becomes

$$\frac{21}{1{,}000{,}000} = 0.000021 = \frac{2.1}{100{,}000} = \frac{2.1}{10^5} = 2.1 \times 10^{-5}.$$

Once again the exponent indicates how we have moved the decimal point. The Sun's mass expressed this way is 1.989×10^{30} kg.

With scientific notation, multiplying and dividing very large numbers becomes easier. This is because when we multiply two powers of 10, we just add the exponents, whereas to divide we subtract them. For example,

$$10^2 \times 10^5 = (10 \times 10) \times (10 \times 10 \times 10 \times 10 \times 10) = 10^{2+5} = 10^7,$$

or as an example of division,

$$\frac{10^8}{10^5} = \frac{10 \times 10 \times 10 \times 10 \times 10 \times 10 \times 10 \times 10}{10 \times 10 \times 10 \times 10 \times 10} = 10 \times 10 \times 10 = 10^{8-5} = 10^3.$$

We can write this as a pair of general rules:

$$10^A \times 10^B = 10^{A+B} \quad \text{and} \quad 10^A/10^B = 10^{A-B}.$$

It is important to remember that $10^A + 10^B$ does *not* equal 10^{A+B}. To add or subtract two numbers expressed in scientific notation, *first* convert both to the *same* power of 10, then add or subtract the values by which the power of 10 is multiplied.

As an illustration of the use of scientific notation, we can calculate the number of kilometers in a light-year. To do this, we multiply light's speed by the number of seconds in a year. A year is 365¼ days, each day having 24 hours, each hour 60 minutes, and each minute 60 seconds, so the total number of seconds in a year is

$$365.25 \text{ days} \times \frac{24 \text{ hours}}{1 \text{ day}} \times \frac{60 \text{ minutes}}{1 \text{ hour}} \times \frac{60 \text{ seconds}}{1 \text{ minute}}$$
$$= 31{,}557{,}600 \text{ seconds} \approx 3.156 \times 10^7 \text{ sec}.$$

The speed of light is 299,793 km/sec = 2.998×10^5 km/sec. Multiplying the speed by the time gives us the distance:

$$\begin{aligned} 1 \text{ ly} &= \text{speed of light} \times 1 \text{ year} \\ &= 2.998 \times 10^5 \text{ km/sec} \times 3.156 \times 10^7 \text{ sec} \\ &= 2.998 \times 3.156 \times 10^{5+7} \text{ km} \\ &\approx 9.46 \times 10^{12} \text{ km}, \end{aligned}$$

or nearly 10 trillion kilometers.

Concept Question 1

How is the phrase "a six-figure salary" like scientific notation? Can you think of other ways we express powers of 10 in everyday usage?

Mathematical Insight

The conversion here is accomplished by multiplying by 1 written in three different ways. Make sure you can identify them.

3.3 SPECIAL UNITS

Even the meter was originally a special unit based on the size of Earth. The original plan was that the meter would be one 10-millionth of the distance from pole to equator. The original determination of the meter was slightly off, however, so that the equator-to-pole distance today is found to be 10,002 km, for a circumference of 40,008 km measured around the poles. More significantly, Earth is not a perfect sphere, so the circumference measured at the equator bulges to 40,075 km.

The enormous range of sizes, masses, and times studied in astronomy is illustrated in Figure 3.4, which provides several examples of objects on scales showing the powers-of-10 value of meters, kilograms, and seconds. While we can always make measurements in terms of these MKS units, it is sometimes easier to grasp the meaning of a value using special units that are more familiar to us.

Few people would understand if someone said he was 700 megaseconds old rather than saying 22 years. A "year" is a special unit that helps us interpret time spans more easily. There are many other places where astronomers have invented units to describe objects and phenomena in a way that is easier to understand. Usually these units make it easier to gain physical intuition, but they add to the number of units to learn, and they are not as easy to convert as metric units.

The **light-year,** the distance light travels in a year, is a good example. In principle we could use metric prefixes and a unit like "petameters" (Table 3.1), and write a light-year as 9.46 petameters or 9.46 Pm. However, the light-year has such a useful interpretation that we prefer to introduce it as another unit. Specifically, when we see an object 10 million light-years away, the light has taken 10 million years to reach us. That means that we are seeing the object *as it was 10 million years ago.* This becomes even more interesting as we look out billions

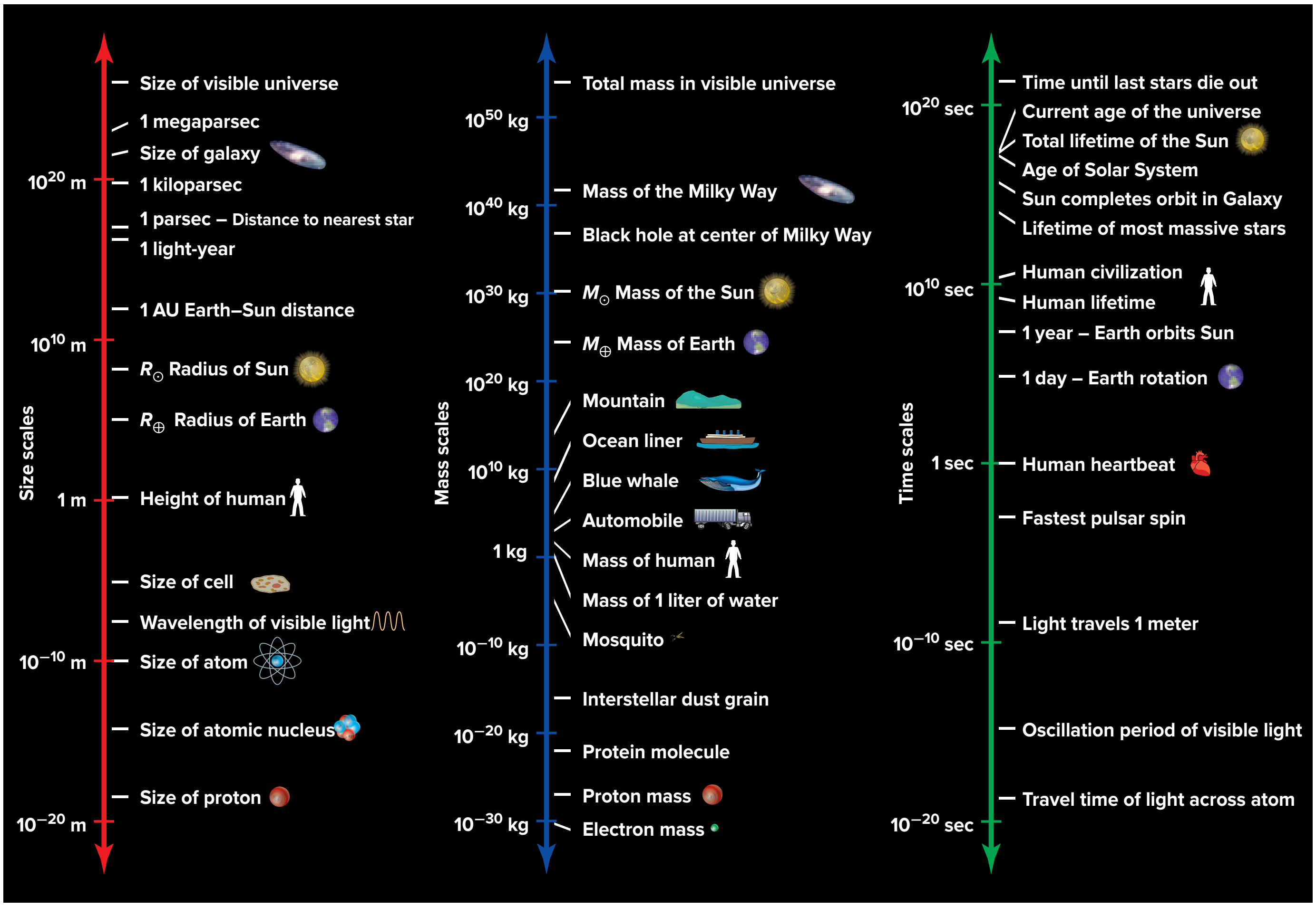


FIGURE 3.4 Scales showing relative sizes, masses, and times of special units and various objects and processes in the universe. Each is shown on a scale of powers of 10—ranging from the submicroscopic to the astronomical.

TABLE 3.3 Special Units

Quantity	Special Unit	Abbreviation	Metric Equivalent
Length	Earth's radius	$R_\oplus$	6.37×10^6 m
	Sun's radius	$R_\odot$	6.97×10^8 m
	Astronomical unit (Earth–Sun distance)	AU	1.50×10^{11} m
	Light-year (distance light travels in one year)	ly	9.46×10^{15} m
	Parsec (distance calculated by special geometric technique)	pc	3.09×10^{16} m
Mass	Earth's mass	$M_\oplus$	5.97×10^{24} kg
	Sun's mass	$M_\odot$	1.99×10^{30} kg
Time	Day (rotation period of Earth)	day	8.64×10^4 sec
	Year (orbital period of Earth)	yr	3.16×10^7 sec
	Sun's lifetime (estimated total time Sun will generate energy)	$t_\odot$	3.16×10^{17} sec
Speed	Speed of light (through empty space)	c	3.00×10^8 m/sec
Acceleration	Earth's surface gravity (the rate at which falling objects accelerate)	g	9.81 m/sec^2
Energy	Kiloton of TNT (energy released by a standard 1000-ton bomb)	kt	4.18×10^{12} joules
Power	Sun's luminosity (energy the Sun generates per second)	$L_\odot$	3.86×10^{26} watts

of light-years, when the universe was just a fraction of its current age. We are literally able to look back toward the beginning of time, and the light-year unit helps us understand what, or rather "when," we are seeing.

A list of the special units we use in this book is given in Table 3.3. Those describing sizes, masses, and times are shown in Figure 3.4. Many of these units are used to relate other objects to the more familiar Sun and Earth, such as the Sun's power output or the length of Earth's year. Some of the units were invented to make our calculations easier. For example, the astronomical unit simplifies the calculation of orbital parameters of objects in the Solar System (Unit 12) as well as of stars that orbit each other (Unit 17). The **parsec** (pc) was invented as a unit to simplify the formula for the primary method we have for finding stars' distances (Unit 54). Both the parsec and light-year are frequently used by astronomers when talking about stars and galaxies, so it is useful to be able to convert back and forth between them. A parsec is a little more than three times larger than a light-year, so converting between them is similar to converting between meters and feet.

For many calculations these special units add an extra step, requiring us to convert the values to the MKS system. For example, suppose we wanted to calculate how fast Earth moves as it orbits the Sun (Figure 3.5). The radius of its orbit is 1 astronomical unit, and it completes an orbit in 1 year. To carry out the calculation, first we need to know how far Earth travels in its orbit. Because the circumference of a circle is 2π times its radius and 1 AU is 1.50×10^{11} meters, we find that Earth travels a distance

$$2 \times \pi \times 1 \text{ AU} = 6.283185 \times 1.50 \times 10^{11} \text{ m} = 9.42 \times 10^{11} \text{ m}$$

in one year, which is a time $= 3.16 \times 10^7$ sec. The speed, V, of Earth is the distance it travels divided by the time, which we calculate as follows:

$$V = \frac{\text{distance}}{\text{time}} = \frac{9.42 \times 10^{11} \text{ m}}{3.16 \times 10^7 \text{ sec}} = 2.98 \times 10^4 \frac{\text{m}}{\text{sec}}.$$

This value is nearly 30 kilometers per second, more than 100,000 kilometers (60,000 miles) per hour. This is about 100 times faster than a speeding bullet!

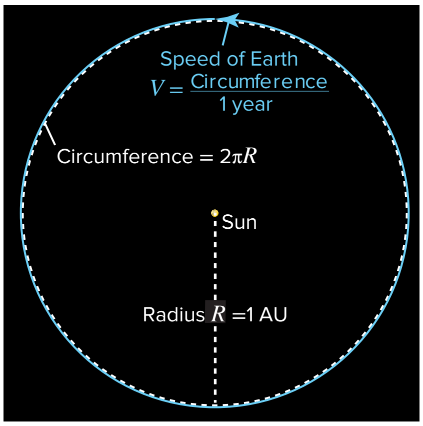


FIGURE 3.5 The speed of Earth as it orbits the Sun is equal to the circumference of its orbit divided by the time it takes to complete the orbit (one year).

3.4 APPROXIMATION

Astronomy is a science in which we often have to make uncertain estimates. Even though we can measure some numbers quite precisely, many others are subject to such uncertainty that there is no point in keeping track of more than the first couple of digits of a number.

For example, astronomers have determined that there are 3.261633 light-years in a parsec. However, we may not know the distance to a star more precisely than to within about 10%. If that star's distance is listed as 1000 parsecs, it is *not* correct to say the star is at a distance of 3261.633 light-years. The latter number gives the appearance of precision that does not exist. It would be more appropriate to convert 1000 parsecs to 3300 light-years or even 3000 light-years—these better reflect the level of precision with which the distance is known.

Mathematical Insight

In the technical literature, astronomers often report numbers with a "plus or minus" range to indicate the uncertainty in a value, like 71 ± 6. Then if we multiplied the number by 2, we would find 142 ± 12, with both the value and the uncertainty doubling. This notation is useful but can become cumbersome when we start multiplying a set of numbers, each of which has its own precision.

Measurements are best reported showing only the number of digits that are accurately known. Values written as 374,000 or 0.00512 or 1.50×10^{11}, for example, are each reported to three **significant digits.** Having three significant digits means that the first two digits (37, 51, 15 in these three examples) are well determined, and the last one is fairly accurate, although it may have some uncertainty. Scientific notation is useful here for indicating when a trailing 0 is significant. This would be unclear if 1.50×10^{11} were written 150,000,000,000.

Any result from multiplying or dividing numbers in a formula can be only as accurate as the *least* accurate measurement used. For example, the nearest star, Proxima Centauri, is measured to be 1.30 parsecs away—to three digits of precision. We can multiply this by the number of light-years per parsec to get the distance in light-years:

$$1.30 \text{ pc} \times \frac{3.261633 \text{ ly}}{\text{pc}} = 4.2401229 \text{ ly} \approx 4.24 \text{ ly}.$$

It makes no sense to give the distance with eight significant digits in light-years when the distance is only known to three significant digits. We **round off** the result to 4.24 ly, with three digits to reflect the level of precision for this calculation.

Notice that because we are limited by the least precise number, there is really no need to use all of the digits 3.261633 in our calculation. If we rounded off our ly-to-pc conversion factor to 3.262, we would have gotten the same result:

$$1.30 \text{ pc} \times \frac{3.262 \text{ ly}}{\text{pc}} = 4.2406 \text{ ly} \approx 4.24 \text{ ly}.$$

If we round off our conversion factor to just one digit, 3, we get:

$$1.30 \text{ pc} \times \frac{3 \text{ ly}}{\text{pc}} = 3.9 \text{ ly} \approx 4 \text{ ly}.$$

The result should be reported to only one digit because one of the numbers we used had only one significant digit. Finally, note that if we round the conversion factor to 3.3, the result is

$$1.30 \text{ pc} \times \frac{3.3 \text{ ly}}{\text{pc}} = 4.29 \text{ ly} \approx 4.3 \text{ ly},$$

which is rounded up to 4.3 because the last digit, 9, is greater than or equal to 5. The correct answer to two significant digits should be 4.2 ly, but when we carry out a calculation with several numbers that are approximate, the result will have a *greater* uncertainty than the least accurate of the numbers.

Concept Question 2

We encounter numbers frequently in everyday life, sometimes exact, sometimes indefinite. What's the most precise number you've encountered? What are some of the most imprecise numbers?

Good use of approximation is an art as well as a science. To be safe, when carrying out a calculation, use as many digits as are available for each value in the equation, and then round off at the end. However, with practice, you will find that you can round off some of the values to fewer digits with no significant effect on the accuracy of your result, making your calculations a little simpler.

KEY POINTS

- Astronomers generally use the metric system.
- Metric prefixes provide a simple way of producing new units of measurement that are useful for different size objects.
- Scientific notation can be used for measurements of any size, and it offers certain conveniences for mathematical calculations.
- Astronomers use several nonmetric units, such as the light-year, that have useful physical meanings or facilitate comparisons.
- Some values are only approximately known in astronomy, and it is important to present values at a level of precision that reflects their accuracy.

KEY TERMS

density, 19
exponent, 18
light-year, 21
metric prefix, 18
metric system, 18
MKS system, 19
parsec, 22
powers of 10, 18
round off, 23
scientific notation, 20
significant digits, 23
unit, 17

CONCEPT QUESTIONS

Concept Questions on the following topics are located in the margins. They invite thinking and discussion beyond the text.

1. Exponentials in common parlance (p. 20)
2. Precise and imprecise numbers (p. 23)

REVIEW QUESTIONS

3. What are the advantages of the metric system?
4. What is meant by a positive exponent? a negative exponent? an exponent of zero?
5. How is a number expressed in scientific notation?
6. What nonmetric units do astronomers frequently use?
7. What are significant digits?
8. When calculations are carried out with several numbers of different precision, what is the precision of the result of the calculation?

QUANTITATIVE PROBLEMS

9. The radius of the Sun is 7×10^5 kilometers, and that of Earth is about 6.4×10^3 kilometers. Show that the Sun's radius is approximately 100 times Earth's radius.
10. Hypergiant stars can have radii as large as 1500 times that of the Sun. Estimate the radius of a hypergiant star in kilometers. How many AU is this equivalent to?
11. Using scientific notation, show that it takes sunlight about 8½ minutes to reach Earth from the Sun.
12. How many 1-kiloton bombs would need to be exploded to produce 3.86×10^{26} joules, the amount of energy emitted by the Sun in 1 second?
13. If I want to work out the distance to the Andromeda Galaxy, do I need to be concerned about whether the distance is from the center of the Milky Way or from the Sun's location? Why or why not?
14. Suppose two galaxies move away from each other at a speed of 6000 km/sec and are 300 million (3×10^8) light-years apart. If their speed has remained constant, how long has it taken them to move that far apart? Express your answer in years.
15. The equation $E = m \times c^2$ tells us how much energy, E, is stored in a mass of m. Use this equation to calculate the energy stored in a 3.10-gram penny.
16. Using scientific notation, evaluate $(1.4 \times 10^9)^3/(9.3 \times 10^8)^2$.
17. Napoleon Bonaparte is often said to have been short, but contemporaries described him as being of average or slightly above-average height for his time. This mistake was apparently made because the height reported in Paris feet was misinterpreted. Bonaparte was reported to be about 5 feet 2 inches tall at his autopsy. If these were in Paris units, 6.63% longer than English inches and feet, how tall was he actually in (a) English units, and (b) metric units?

TEST YOURSELF

18. Which of the following is the correct method for calculating $10^5/10^3$?
    a. 10^{5+3}
    b. 10^{5-3}
    c. $10^{5\times3}$
    d. $10^{5/3}$
    e. $10^{(5+3)/2}$
19. Which of the following is *not* equivalent to 30 kilometers?
    a. 30,000,000 millimeters
    b. 3×10^6 cm
    c. 30,000 meters
    d. 3×10^3 meters
    e. 0.03 megameters
20. From the following, choose the best approximation for the sum of 3.14×10^{-1} and 6.86×10^4.
    a. 10.00×10^3
    b. 6.86×10^4
    c. 3.14×10^{-1}
    d. 1.00×10^3
    e. 3.72×10^3
21. Which of the following numbers has 3 significant digits?
    a. 33,300
    b. 3×10^3
    c. 0.033
    d. 330.000
    e. 3.000×10^3
22. There are 1.61 kilometers in a mile, and 3600 seconds in an hour. How would you convert 30 km/sec to miles per hour?
    a. Multiply 30 by 1.61, then divide it by 3600.
    b. Divide 30 by 1.61, then divide it by 3600.
    c. Multiply 30 by 1.61, then multiply it by 3600.
    d. Divide 30 by 1.61, then multiply it by 3600.