

ASTRONOMY

THE UNIVERSE AT A GLANCE



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THE UNIVERSE AT A GLANCE

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Library of Congress Cataloging-in-Publication Data

Chaisson, Eric.

Astronomy : the universe at a glance / Eric Chaisson, Harvard University, Steve McMillan, Drexel University.
pages cm

Includes bibliographical references and index.

ISBN 978-0-321-79976-0 — ISBN 0-321-79976-3

1. Astronomy—Textbooks. I. McMillan, S. (Stephen), 1955– II. Title.

QB43.3.C47 2016

520—dc23

2014041645

ISBN 10: 0-321-79976-3; ISBN 13: 978-0-321-79976-0 (Student edition)

PEARSON

www.pearsonhighered.com

1 2 3 4 5 6 7 8 9 10—V011—16 15 14 13 12

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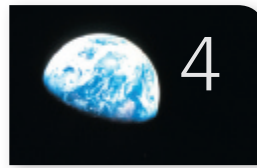
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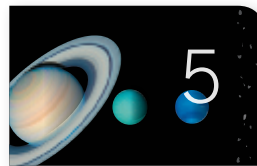
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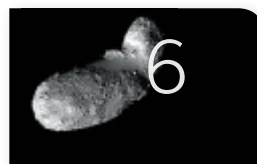
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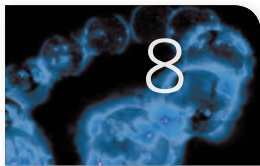
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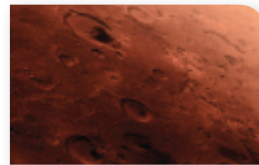
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ABOUT THE AUTHORS



Eric Chaisson

Eric holds a doctorate in astrophysics from Harvard University, where he spent 10 years on the faculty of Arts and Sciences. For more than two decades thereafter, he served on the senior science staff at the Space Telescope Science Institute and held various professorships at Johns Hopkins and Tufts universities. He is now back at Harvard, where he teaches and conducts research at the Harvard-Smithsonian Center for Astrophysics. Eric has written 12 books on astronomy and has published nearly 200 scientific papers in professional journals.



Steve McMillan

Steve holds a bachelor's and master's degree in mathematics from Cambridge University and a doctorate in astronomy from Harvard University. He held postdoctoral positions at the University of Illinois and Northwestern University, where he continued his research in theoretical astrophysics, star clusters, and high-performance computing. Steve is currently Distinguished Professor of Physics at Drexel University and a frequent visiting researcher at Princeton's Institute for Advanced Study and Leiden University. He has published more than 100 articles and scientific papers in professional journals.

PREFACE

Astronomy is enjoying a golden age of exploration and discovery. Fueled by new technologies and novel theoretical insights, the study of the cosmos has never been more exciting than it is right now. We are pleased to have the opportunity to present in this book a carefully chosen selection of the known facts, evolving ideas, and frontier discoveries in astronomy today.

In *Astronomy: The Universe at a Glance*, we have tried to combine a narrative that is both accurate and approachable with a visually compelling presentation that fosters learning. To that end, we have created a short (275-page) book in which we have taken the novel step of subdividing the material so that each new discussion topic fits precisely into a single two-page spread. This modular approach integrates art and text into a magazine-style format that is visually stunning, succinct, and scientifically correct. Although we have had to pare back or omit some topics, we think the final result captures the essence of 21st-century astronomy in a beautiful—and highly teachable—way. We have taken particular care to show how science is done, how the universe works, and how astronomers know what they know. In the process, we highlight both the scientific principles underlying scientific inquiry and the process of discovery.

Our organization follows the popular and effective “Earth out” progression. We have found that most students, especially those with little scientific background, are much more comfortable studying the relatively familiar solar system before tackling stars and galaxies. With Earth and the Moon as our initial planetary models, we move through the solar system, discussing both its content and its formation. This line leads directly to a study of the Sun. With the Sun as our model star, we broaden the discussion to include stars in general—their properties, their evolutionary histories, their varied fates. The journey then leads us to study the Milky Way Galaxy, which in turn serves as an introduction to other galaxies. Finally, we reach cosmology and the large-scale

structure and dynamics of the universe as a whole. Throughout, we strive to emphasize the dynamic nature of the cosmos—virtually every major topic, from planets to quasars, includes a discussion of how those objects formed and how they evolve.

We place much of the needed physics in the early chapters—an approach derived from years of experience teaching thousands of students. Additional physical principles are developed as needed later in the book, both in the text and in the *Snapshot* boxes (described on p. xv). We have made the treatment of physics, as well as the more quantitative discussions, as modular as possible so that these topics can be omitted or assigned separately, as desired.

This book has been written for students who have taken no previous college science courses and who will likely not major in physics or astronomy. It is intended for use in a one-semester, nontechnical astronomy course. We present a broad view of astronomy, straightforwardly and without complex mathematics. We rely on qualitative reasoning, as well as analogies to objects and phenomena familiar to students, to explain the complexities of the subject without oversimplification. We have tried to both communicate the excitement we feel about astronomy and awaken students to the magnificent universe around us.

In teaching astronomy to nonscientists, as in writing this book, we are not seeking to convert students to careers in astronomy or even science in general. Instead, we strive to reach the wider audience of students who are majoring in many other worthwhile fields. We want to encourage those students to become scientifically literate members of modern society, to appreciate new developments in the world of science, and to understand what scientists do for a living to enable them to make informed judgments regarding national initiatives in science and to vote intelligently in our democratic, increasingly technological world.



Acknowledgments

The publishing team at Pearson has assisted us at every step along the way in creating this innovative text. We owe huge debts of gratitude to Development Editor Barbara Price, who with great enthusiasm and passion almost single-handedly brought to life the design and layout of this book, and to Project Manager Tema Goodwin, who managed with unflappable aplomb and unerring judgment the many variables that go into a multifaceted publication such as this. Production Managers Angela Urquhart and Andrea Archer of Thistle Hill Publishing Services, Designer Tamara Newnam, LuAnn Murphy of Rolin Graphics, and Photo Researcher Cordes McMahan Hoffman of QBS Learning have excelled in tying together the threads of this complex project, made all the more so by the necessity of combining text, art, photos, and electronic media into a coherent whole. Special thanks are also in order to Design Director

Mark Ong for making this first edition so spectacular and to Acquisitions Editor Nancy Whilton for supporting this grand experiment.

We would also like to express our gratitude to Kate Brayton and Ziki Dekel for creating and maintaining the media resources in the MasteringAstronomy® Study Area.

Throughout the development and production of this book, we have relied on the critical analysis of many colleagues and reviewers. Their suggestions have ranged from the macroscopic issue of the book's overall organization to the minutiae of the technical accuracy of each and every sentence. To all, we offer our sincerest thanks.

Eric Chaisson

Steve McMillan

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LEARNING AT A GLANCE

A Modular Approach to Teaching Astronomy

Visually Driven Modular Learning

This new book by trusted authors Eric Chaisson and Steve McMillan reimagines their classic texts in a modularly organized, visual approach to learning. Here, the essential ideas, concepts, and discoveries of contemporary astronomy are presented in 15 chapters, each chapter composed of richly illustrated, two-page spreads designed to visually engage and instruct students.

Learning Outcomes:

Navigation Tools for Student Success

Studies indicate that beginning students have trouble prioritizing textual material. For this reason, six to eight well-defined, numbered Learning Outcomes are provided at the start of each chapter. Since each Learning Outcome is keyed to a specific, numbered section in the chapter, students can see at a glance the roadmap to discovery.

This unique modular structure helps students organize their reading and test their mastery of key concepts. The Learning Outcomes are also keyed to items in the Chapter Review Summary and to assessments at the end of each chapter. This highlighting of the most important aspects of the chapter helps students prioritize and review information.

The book's modular structure is also helpful to instructors.

Because each Learning Outcome is keyed to a unique two-page spread, instructors can easily select topics, or rearrange the order of topics, with a quick review of the Learning Outcomes listed at the beginning of each chapter. In this way, instructors can adapt this book for courses taught over a semester, a quarter, or a summer.

6 SMALL BODIES IN THE SOLAR SYSTEM

The moons and rings of the jovian planets and interplanetary debris add fascinating variety to the solar system.

All four jovian planets have systems of moons and rings that exhibit fascinating variety and complexity. The six largest jovian moons have many planetary features, providing us with insight into the terrestrial worlds. Two of these moons, Jupiter's Europa and Saturn's Titan, have become prime candidates for study in the search for life elsewhere in the solar system.

Like the moons, the rings of the jovian planets also differ greatly. The rings of Saturn—the largest and best-known ring system among the jovian planets—are one of the most spectacular displays in the sky.

Between Mars and Jupiter orbit countless small rocky bodies thought to be left over from the formation of the solar system. Beyond the orbit of Neptune, the solar system consists of small icy bodies having much in common with the large jovian moons and little similarity to the eight major planets. For these reasons we study all these objects here, along with the moons and rings of their giant neighbors.

6.2 Io: A Moon of Volcanoes

Io is the most volcanically active body in the entire solar system.

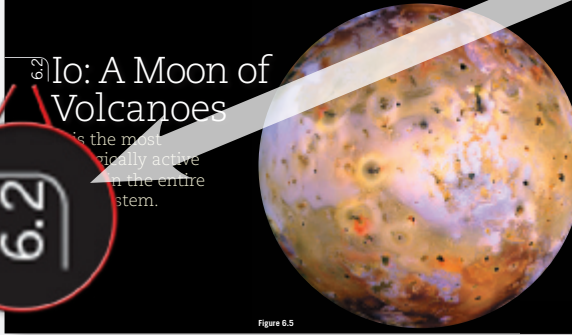


Figure 6.5 Io is the most volcanically active body in the entire solar system. This collage shows several volcanic sites—the red-tinted areas are the most easily identified. Note especially the large volcanic region (Gallio Pelt) at the 8 o'clock position on the horizon.

In mass and radius, Io is similar to Earth's Moon, but there the resemblance ends. Io's bizarre uncratered surface (Figure 6.5) is a collage of yellows, oranges, and blackish-browns—resembling a giant pizza in the minds of some startled Voyager scientist!

Spying on Io

As Voyager 1 sped past Io, it made an outstanding discovery: Io has active volcanoes! The spacecraft photographed eight erupting volcanoes. Six of them were still erupting when Voyager 2 passed by 4 months later. The Galileo mosaic in Figure 6.5 shows several volcanic sites—the red-tinted areas are the most easily identified. Note especially the large volcanic region (Gallio Pelt) at the 8 o'clock position on the horizon.

Figure 6.6 is a close-up view of a volcanic region, obtained by Voyager 1 during its 1979 flyby. The volcano is the dark oval region at right. The dark lava flow extends toward the lower left for about 300 km long. The orange color immediately surrounding the volcanoes most likely results from sulfur compounds in the ejected material. Io's smooth surface is the result of molten matter constantly filling in any "dents and cracks" caused by impact craters or other surface phenomena. Io has a thin atmosphere composed mainly of sulfur dioxide produced by volcanic activity and temporarily retained by the moon's gravity.

By the time Galileo reached the Jupiter system, some of the volcanoes observed by Voyager 2 had subsided, but many new ones were seen—in fact, Galileo found that Io's surface features can change significantly in as little as a few weeks. In all, more than 80 active volcanoes have been identified on Io. The largest (known as Loki, and located on the "back" side of Io in Figure 6.5) is larger than the state of Maryland and emits more energy than all of Earth's volcanoes combined.

According to Galileo's sensors, lava temperatures on Io generally range from 650 to 900 K, although temperatures as high as 2000 K—far hotter than any earthly volcano—have been measured at some locations. Mission scientists speculate that these superhot volcanoes may be similar to those that occurred on Earth some 3 billion years ago.

The Voyager flybys didn't have the luxury of waiting for the perfect shot. They photographed what they saw and then moved on to their next target, Saturn. However, Galileo spent years in the Jupiter system, repeatedly visiting its many moons, and it returned some spectacular views of Io's volcanoes caught in the act of erupting (Figure 6.7). The left inset in Figure 6.7 shows a volcano called Prometheus ejecting matter at speeds of up to 2 km/s to an altitude of about 150 km.

Instead, just as we saw in the case of Europa, the source of Io's energy is external—Jupiter's gravity. Because Io orbits closer to Jupiter than does Europa, the planet's huge gravitational field produces much stronger tidal forces on Io than on Europa, resulting in a large (100 m) tidal bulge (see Section 5.5). At the same time, the gravity of its nearest large neighbor Europa disturbs its circular synchronous orbit, causing it to wobble slightly from side to side on its axis as it moves.

The conflicting forces acting on Io result in enormous tidal stresses that continually squeeze and heat its interior. Researchers estimate that the total amount of heat generated within Io as a result of tidal flexing is about 100 million megawatts—five times the total power consumption of all the nations on Earth. The large amount of heat generated within Io causes huge jets of gas and molten rock to squirt out of the surface. It is likely that much of Io's interior is soft and molten, with only a relatively thin solid crust overlying it.

Io's volcanism has a major effect on Jupiter's magnetosphere. The planet's magnetic field continually sweeps past Io, gathering up the charged particles its volcanoes spew into space and accelerating them to high speed. The result is the Io plasma torus (Figure 6.8), a doughnut-shaped region of energetic particles following Io's orbital track and completely encircling the planet. It is both a significant source of radio emission and a formidable radiation hazard to visiting spacecraft.

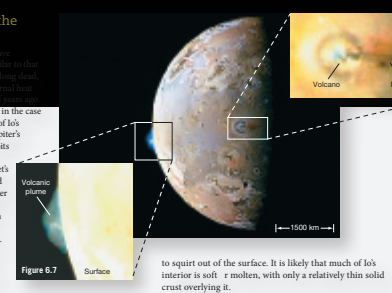


Figure 6.7 Io's volcanism has a major effect on Jupiter's magnetosphere. The planet's magnetic field continually sweeps past Io, gathering up the charged particles its volcanoes spew into space and accelerating them to high speed. The result is the Io plasma torus (Figure 6.8), a doughnut-shaped region of energetic particles following Io's orbital track and completely encircling the planet. It is both a significant source of radio emission and a formidable radiation hazard to visiting spacecraft.

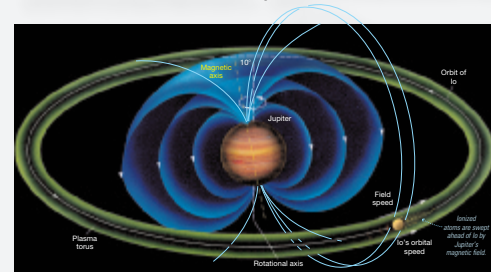


Figure 6.8 The Io plasma torus is a doughnut-shaped region of energetic particles following Io's orbital track and completely encircling the planet. It is both a significant source of radio emission and a formidable radiation hazard to visiting spacecraft.

End-of-Chapter Assessment

- Each chapter incorporates Review and Discussion Questions, which may be assigned or used for in-class review. As with the True/False and Multiple Choice Questions, the material needed to answer Review Questions can be found within the chapter. Questions identified with a **POS** icon encourage students to explore the Process of Science, and those flagged with a **VIS** icon are tied directly to a specific figure or diagram in the text.
- Each Learning Outcome is matched to an assessment at the end of each chapter and is identified by number and the icon **LO**.
- The end-of-chapter material ends with collaborative and individual Activities relevant to the material presented in the text. These range from basic naked-eye and telescopic observation projects to surveys, group discussions, and astronomical research on the Web.

Chapter Review Summaries

The Chapter Review Summary, a primary review tool, is linked to the Learning Outcomes at the beginning of each chapter. Key Terms introduced in each chapter are listed again, in context and in boldface, along with key figures and page references to the text discussion.

Each Learning Outcome is matched to a specific two-page spread

Learning Outcomes map to chapter summaries and assessments

Learning Outcomes for this chapter are:

- LO1** Describe how the Galilean moons form a miniature solar system around Jupiter and exhibit a wide range of properties.
- LO2** Present the evidence for ongoing volcanism on Jupiter's moon Io, and explain what causes it.
- LO3** Describe the composition and likely origin of the atmosphere on Titan, Saturn's largest moon.
- LO4** Outline the properties of the medium-sized moons of the outer planets.
- LO5** Discuss the nature and detailed structure of Saturn's rings.
- LO6** Explain how planetary rings form and evolve, and list the major differences between the rings of Saturn and those of the other jovian planets.
- LO7** Describe the composition of the solar system beyond Neptune, and explain why astronomers no longer regard Pluto as a planet.
- LO8** Compare and contrast the physical and orbital properties of asteroids and comets.

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The potato-shaped asteroid Itokawa orbits between Mars and Jupiter and is only 0.5 km—about five football fields—long. As asteroids go, it's pretty typical. The Japanese spacecraft Hayabusa soft-landed here in 2005, scooped up some rocky debris, and returned it to Earth in 2010. The mission proved that asteroids are the source of most meteorites—the oldest matter in the

CHAPTER 2 REVIEW

Chapter Summary

- LO1** Visible light (p. 21) is a particular type of electromagnetic radiation (p. 20) and travels through space in the form of a wave (p. 21). A wave is characterized by its period (p. 21), the length of time taken for one complete cycle; its wavelength (p. 21), the distance between successive wave crests; and its amplitude, which measures the size of the disturbance associated with the wave. A wave frequency (p. 21) counts the number of wave crests passing a given point in one second.
- LO2** A beam of white light is bent, or refracted, as it passes through a prism. Different frequencies of light are refracted by different amounts, splitting light into its component colors—the visible spectrum. Light with a shorter wavelength—red light has a longer wavelength—red light has a longer wavelength. The entire electromagnetic spectrum consists of (in order of increasing frequency) radio waves, microwaves, infrared radiation, visible light, ultraviolet, X-rays, and gamma rays (p. 21).
- LO3** An object has a temperature if it emits electromagnetic radiation. The intensity of its radiation depends on its temperature, called a blackbody curve. A blackbody curve depends only on the object's temperature.
- LO4** A telescope (p. 26) is a device that collects light from a distant object and focuses it into its component frequencies and displaying them on a screen or detector for detailed study. Many hot objects emit a continuous spectrum of radiation, containing light of all wavelengths. A hot gas may instead produce an emission spectrum, consisting of only a few well-defined emission lines (p. 26) of specific frequencies, or colors. Passing a continuous beam of radiation through cool gas will produce absorption lines (p. 27) at precisely the same frequencies as are present in the gas's emission spectrum.
- LO5** Atoms (p. 28) are made up of negatively charged electrons orbiting a positively charged heavy nucleus (p. 28) consisting of positively charged protons (p. 28) and electrically neutral neutrons (p. 28). An electron moves between energy levels within

an atom, the difference in energy is emitted or absorbed in the form of electromagnetic radiation. More complex atoms generally produce a continuous spectrum of light. A telescope (p. 30) is a device designed to collect as much light as possible from some distant object and deliver it to a detector. Large astronomical telescopes collect light, because large mirrors gather light and easier to construct than large lenses. The light-gathering power of a telescope depends on its collecting area (p. 30), which is proportional to the square of the mirror diameter. To study the faintest sources of radiation, astronomers must use large telescopes. Big telescopes can also achieve better angular resolution (p. 30) once the blurring effects of Earth's atmosphere are overcome.
- LO7** Radio telescopes (p. 32) are conceptually similar in construction to optical refracting telescopes. However, they are generally much larger than optical instruments, very little radio radiation reaches Earth from space, so large collecting areas are essential. Their main disadvantage is the limited resolution attainable using long-wavelength radio waves. Working together in arrays, as an interferometer (p. 33), radio telescopes can overcome this limitation, achieving superb resolution. Their principal advantage is that they allow astronomers to explore a whole new part of the electromagnetic spectrum and of the universe—many radio sources are completely undetectable in visible light.
- LO8** Infrared telescopes and ultraviolet telescopes are generally similar in design to optical systems. Studies undertaken in some parts of the infrared range can be carried out using large ground-based systems. Ultraviolet astronomy must be done from space. High-energy telescopes, which study X-ray and gamma-ray regions of the electromagnetic spectrum, also must be done from space. Earth's atmosphere is opaque at all these short wavelengths. X-ray telescopes can form images of their field of view, although the mirror design is more complex than optical instruments. Gamma-ray telescopes simply point in certain directions and count the photons they collect.

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Problems labeled **POS** explore the process of science | **VIS** problems focus on reading and interpreting visual information
LO problems focus on learning outcomes

Review and Discussion

1. What is a wave?
2. Describe the way in which light leaves a star, travels through the vacuum of space, and finally is seen by someone on Earth.
3. Name the colors that combine to make white light. What is it about the various colors that causes us to perceive them differently?
4. What do radio waves, infrared radiation, visible light, ultraviolet radiation, X-rays, and gamma rays have in common? How do they differ?
5. How do astronomers use the Doppler effect to determine the velocities of astronomical objects?
6. If Earth were completely blanketed with clouds and we couldn't see the sky, could we learn about the realm beyond the clouds? What forms of radiation might be received?
7. In terms of its blackbody curve, describe what happens as a red-hot glowing coal cools.
8. **LO8** What is spectroscopy? Explain how astronomers might use spectroscopy to determine the composition and temperature of a star.
9. What is a photon?
10. **LO8** Why do excited atoms absorb and reemit radiation at characteristic frequencies?
11. Explain how a beam of light passing through a diffuse cloud may give rise to both absorption and emission spectra.
12. **LO8** Why do astronomers want their telescopes to be as large as possible?
13. How does Earth's atmosphere affect what is seen through an optical telescope?
14. **LO7** Which astronomical objects are best studied with radio techniques?
15. What is interferometry, and what problem in radio astronomy does it address?
16. **LO8** **POS** What are the main advantages of studying objects of many different wavelengths of radiation?

True/False

1. A blackbody emits all its radiation at a single frequency.
2. Earth's atmosphere is transparent to all forms of electromagnetic radiation.
3. The peak of an object's emitted radiation occurs at a frequency determined by the object's temperature.
4. Imagine an emission spectrum produced by a container of hydrogen gas. Changing the amount of hydrogen in the container will change the colors of the lines in the spectrum.

Multiple Choice

1. Compared with ultraviolet radiation, infrared radiation has greater (a) wavelength; (b) amplitude; (c) frequency; (d) energy.
2. A star much cooler than the Sun would appear (a) red; (b) blue; (c) smaller; (d) larger.
3. The blackbody curve of a star moving toward Earth would have its peak shifted (a) to a higher intensity; (b) toward higher energies; (c) toward longer wavelengths; (d) to a lower intensity.
4. Compared with a ground-based spectrum, the spectrum of a star observed from above Earth's atmosphere would show (a) no absorption lines; (b) fewer emission lines; (c) fewer absorption lines; (d) many more absorption lines.
5. Astronomers analyze starlight to determine a star's (a) temperature; (b) composition; (c) motion; (d) all of the above.
6. The primary reason professional observatories are built on the highest mountaintops is to (a) get away from city lights; (b) be above the rain clouds; (c) reduce atmospheric blurring; (d) improve chromatic aberration.
7. Compared with radio telescopes, optical telescopes can (a) see through clouds; (b) be used during the daytime; (c) resolve finer detail; (d) penetrate interstellar dust.
8. The best way to study young stars hidden behind interstellar dust clouds would be to use (a) X-rays; (b) infrared light; (c) ultraviolet light; (d) blue light.

Activities

- Collaborative** Find a spectrum of the Sun that also has a wavelength scale on it. Google is a good place to start. Select some absorption lines and determine their wavelengths by interpolation. Now try to identify the elements that produced these lines. Work with the darkest lines before trying the fainter ones. How many different elements can you find?
- Individual** Locate the constellation Orion in the winter sky. Its two brightest stars are Betelgeuse and Rigel. Which is hotter? How can you tell? Which of the other stars scattered across the sky are hot, and which are cool?

A Visually Driven Textbook for Today's Students

Today's students are highly visual, efficient learners. This textbook, with its magnificent art program and attractive, magazine-style design, appeals to students who want information that is concise and visually engaging. With that as their goal, the authors have also constructed a beautifully written narrative, distilling the essentials of each topic in a text that is both authoritative and accessible to non-science majors.

The Latest Content

From climate change on Earth, to on-going space missions inside the solar system, to the search for life on distant planets, astronomy is often in the headlines. In the process of writing this book, the authors relied on the most recent astronomical discoveries and data to bring students the latest information about the universe and our place in it.

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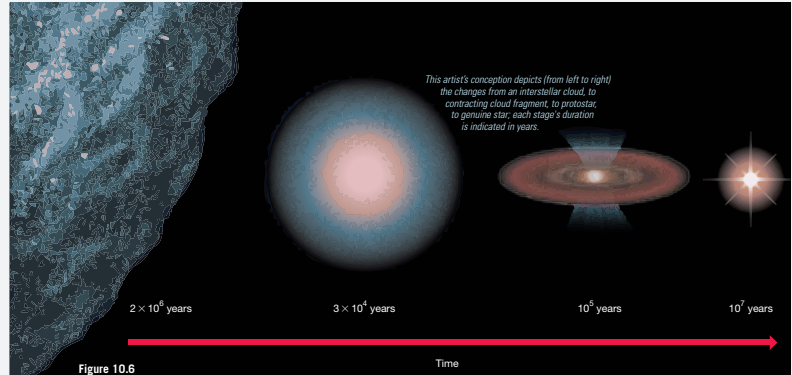


Figure 10.6

Protostars

Now, for the first time, one or more of the fragments begin to resemble a star. A dense, opaque region at the center of each fragment is called a **protostar**—an embryonic object perched at the dawn of star birth; yet its mass continues increasing as more and more matter rains down on it from the outside. Its radius also continues shrinking because its internal heat is not yet enough for its gas pressure to compete with the relentless pull of gravity. Figure 10.6 artistically depicts the emergence of one such protostar from its parent interstellar cloud.

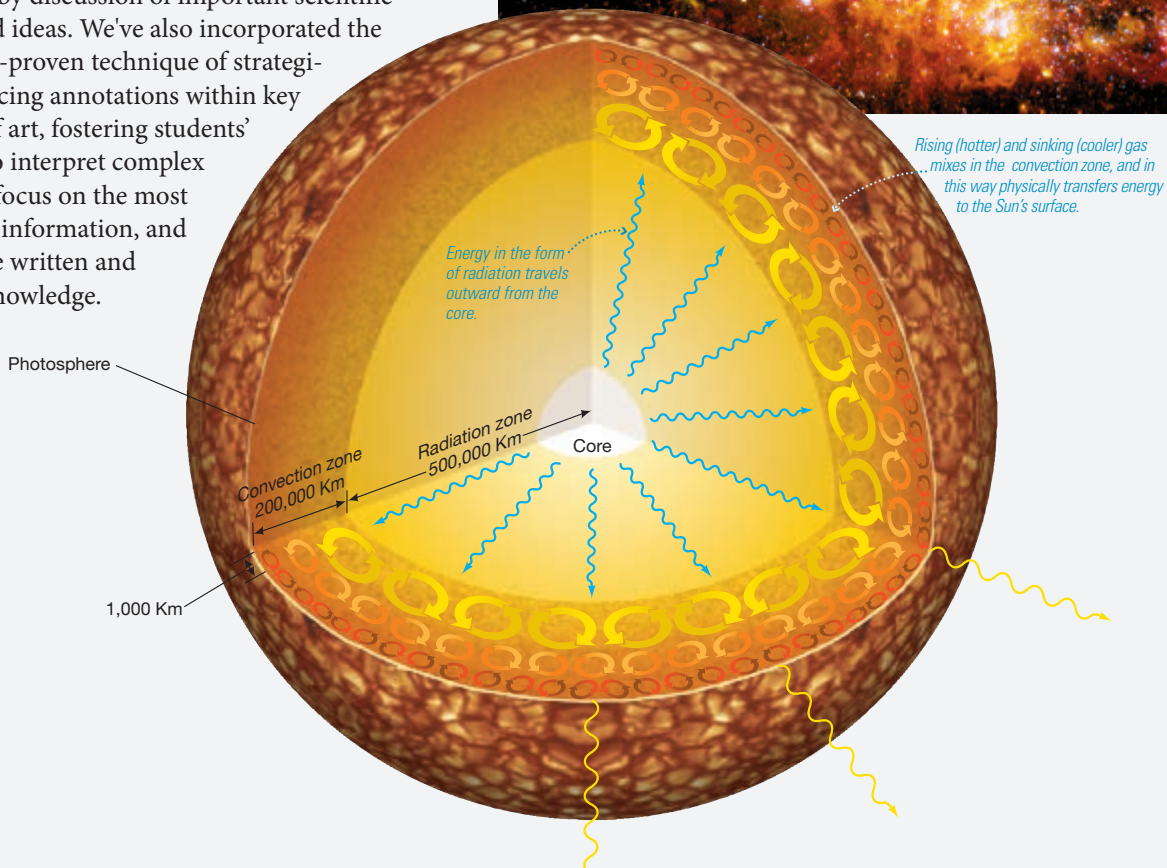
About 100,000 years after the fragment first formed, its central temperature has soared to a seething 1,000,000 K. Electrons and protons ripped from its atoms whiz around at great speeds, but even this temperature is short of the 10^7 K needed to ignite the proton-proton nuclear reactions that fuse hydrogen into helium. Still much larger than our Sun, this gassy heap is now about the size of Mercury's orbit.

A protostar is not well balanced—its contraction slows but does not stop completely. All the while, it often exhibits

violent surface activity, resulting in protostellar winds a little like our Sun's solar wind today, but much stronger and denser. The interaction between the energetic winds and the nebular disk out of which the protostar (and possibly planets) has formed often results in a bipolar flow—expelling two “jets” of matter perpendicular to the disk. This is illustrated toward the right of Figure 10.6.

Some 10 million years after it first began forming, the protostar finally becomes a true star. Protons begin fusing into helium nuclei in the core, and a star is born. Over the next 30 million years, it will contract a little more, adjusting its properties slightly and bringing its core to 15,000,000 K and its surface to 6000 K, much as for the Sun today.

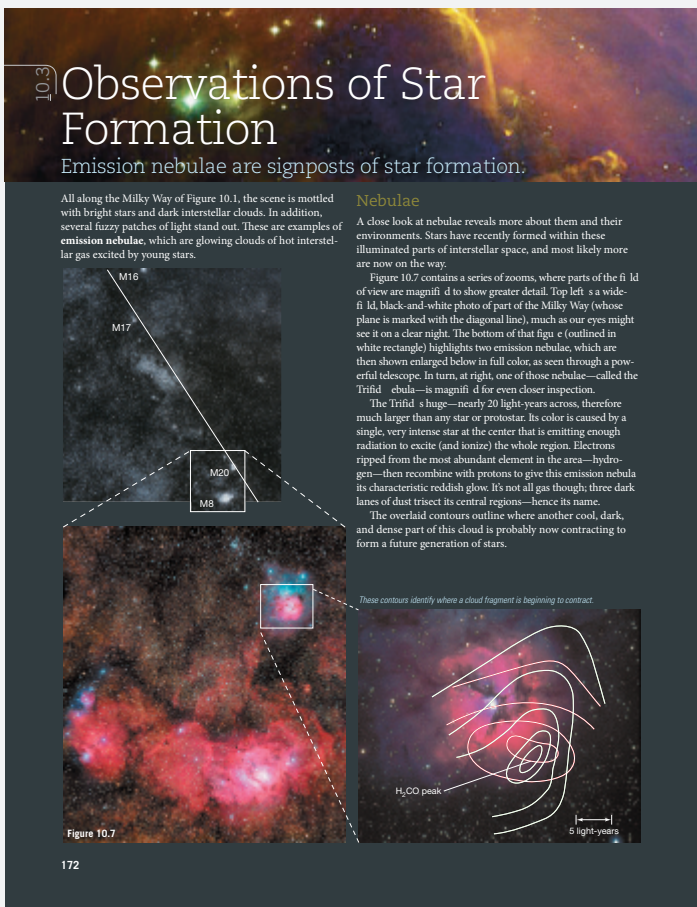
The journey from interstellar cloud to genuine star occurs over the course of 40–50 million years. Although this is a long time by human standards, it is still less than 1 percent of the Sun's lifetime as a star. Once such an object begins fusing hydrogen and establishes a “gravity-in/pressure-out” equilibrium, it burns steadily for a very long time. It will remain almost unchanged for the next 10 billion years.



Compound Art

It is rare that a single image, be it a photograph or an artist's conception, can capture all aspects of a complex subject. Wherever possible, multiple-part figures are used in an attempt to convey the greatest amount of information in the most vivid way:

- Breakouts—often multiple ones—are used to zoom in from wide-field shots to close-ups so that detailed images can be understood in their larger context.
- Stepped art and timelines summarize processes and events.
- Interpretive line drawings are often superimposed on or juxtaposed with real astronomical photographs, helping students to really “see” what the photographs reveal.



Protostar Observations

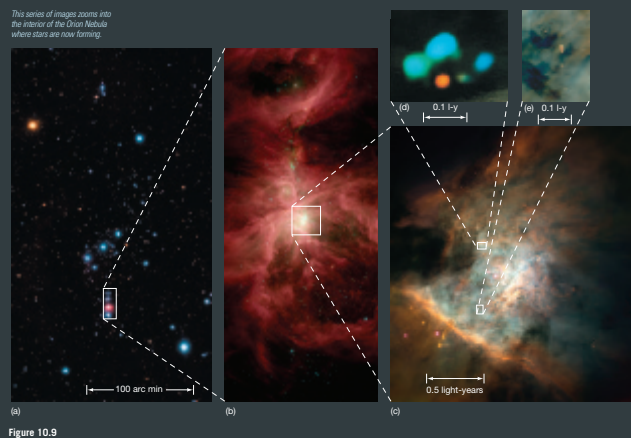
Figure 10.9 shows another star-forming region. This is the famous Orion Nebula wherein many stars are now emerging from the messy hodgepodge of interstellar gas and dust. Not only that, protostars seem to be present—as well as dense and dusty disks around them where planets may well be forming.

The Orion Nebula is part of the large Orion (“the hunter”) constellation that can be easily spotted in the winter sky. The nebula itself spans several light-years across, and at about 1400 light-years away it is the closest of the well-known star-forming regions—hence we can observe it especially well.

As shown in Figure 10.9(a), the nebula itself resides within the white rectangle below the belt of three bright blue stars. When magnified in part (b), the extended nebula glows in the infrared, which emphasizes regions of heated dust. A further enlargement of the central part of the nebula is shown in part (c), this one in true color as our human eyes would see it (if we had telescopic vision). All through this remarkable *Hubble Space Telescope* image, and illustrated here by the two insets in part (c), are embedded nebular “knots” thought to harbor protostars.

Figure 10.8 might actually show direct evidence for protostars themselves. This pair of images is highly magnified, displaying disks that have dimensions of our Solar System, well less than a light-year. The image at left shows a disk edge-on; the one at the right looks down onto the face of another disk. The newly formed stars, or protostars, are still engulfed by much dirty dust, probably enriched in heavy elements and possibly accreting to form planets.

Two decades ago, astronomers had only vague ideas about how and where stars form. Now, with modern telescopes and powerful computer simulations, much more is understood about this most fundamental process.



Snapshot Boxes

Consistent with the modular construction of this book, the Snapshot Boxes encapsulate topics that are related to, but are not part of, the main narrative in each section. These asides might expand upon a particular discovery, showcase the process of science, describe an event in the history of science, or provide supplementary material on topics of current interest.

H–R Diagrams

All of the book’s H–R diagrams are drawn in a uniform format, using real data.

Snapshot 12-2 GEOMETRY OF CURVED SPACE

Euclidean geometry is the geometry of flat space—like that taught in high schools everywhere. Set forth by Euclid, one of the greatest of the ancient Greek mathematicians, it is the geometry of everyday experience. Houses are built with flat floors. Writing tablets and blackboards are also flat. We work easily with flat, straight objects because a straight line is the shortest distance between any two points.

In reality, the geometry of Earth’s surface is not flat. It’s curved. We live on a sphere, and on its surface Euclidean geometry breaks down. Instead, the rules are those of Riemannian geometry, named after a 19th-century German mathematician. There are no parallel lines on the surface of a sphere, the sum of the angles of a triangle is more than 180° (not exactly 180° as in flat space), and the circumference of a circle is less than π times its diameter. Aircraft navigators know this well, as aircraft generally fly on “great circles” on Earth. Many other non-Euclidean geometries are known, such as the negatively curved saddle surface illustrated at right.

Knowledge of non-Euclidean geometries is essential in dealing with black holes. Without it, we would have no hope of understanding these strange objects.

Flat space is governed by Euclidean geometry...

Sum of angles = 180°

... positively curved space by Riemannian geometry...

Sum of angles greater than 180°

Greenland
Shortest path

Los Angeles New York London

London
Shortest path

Los Angeles New York London

... and negatively curved space by Lobachevsky geometry.

Sum of angles less than 180°

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Timothy F. Slater, *University of Wyoming*

Jeffrey P. Adams, *Millersville University*

Strategies for ASTRO 101 is a guide for instructors of the introductory astronomy course for nonscience majors. Written by

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two leaders in astronomy education research, this book details various techniques instructors can use to increase students' understanding and retention of astronomy topics, with an emphasis on making the lecture a forum for active student participation. Drawing from the large body of recent research to discover how students learn, this guide describes the application of multiple classroom-tested techniques to the task of teaching astronomy to predominantly nonscience students.
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