Jay M. Pasachoff Alex Filippenko

# The Cosmos: Astronomy in the New Millennium

Second Edition

# The Cosmos:

# **Astronomy in the New Millennium**

SECOND EDITION

Jay M. Pasachoff
WILLIAMS COLLEGE

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University of California, Berkeley

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visible in the background.

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Paraninfo Calle Magallanes, 25 28015 Madrid Spain stronomy continues to flourish. The pair of Keck 10-meter-diameter telescopes in Hawaii and the quartet of 8-meter-diameter telescopes in Chile called the Very Large Telescope are among the instruments used to make important discoveries from mountaintop observatories. Still larger telescopes are on the drawing board. The Hubble Space Telescope sends down exciting data all the time. The latest major space observatories send down images made with gamma rays, with x-rays, and with infrared radiation. The overall structure of the Universe is being mapped and analyzed, with catalogues of millions of objects being compiled. Further, new electronic instruments and computer capabilities, new space missions to Solar-System objects, and advances in computational astronomy and in theory will continue to bring forth exciting results.

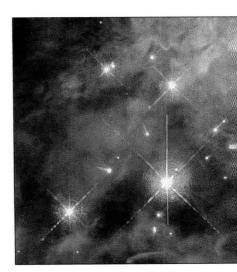
In *The Cosmos: Astronomy in the New Millennium*, we describe the current state of astronomy, both the fundamentals of astronomical knowledge that have been built up over decades and the incredible advances that are now taking place. We want simply to share with you the excitement and magnificence of the Universe. We try to cover all the branches of astronomy without slighting any of them; each teacher and each student may well find special interests that are different from our own. One of our aims in writing this book is to educate voters and prospective voters in the hope that they will understand the value and methods of scientific research in general and astronomical research in particular.

In writing this book we share the goals of a commission of the Association of American Colleges, whose report on the college curriculum stated, "A person who understands what science is recognizes that scientific concepts are created by acts of human intelligence and imagination; comprehends the distinction between observation and inference and between the occasional role of accidental discovery in scientific investigation and the deliberate strategy of forming and testing hypotheses; understands how theories are formed, tested, validated, and accorded provisional acceptance; and discriminates between conclusions that rest on unverified assertion and those that are developed from the application of scientific reasoning." The scientific method permeates the book.

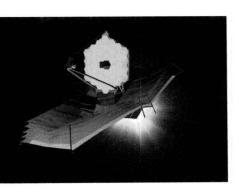
What is science? The following statement was originally drafted by the Panel on Public Affairs of the American Physical Society, in an attempt to meet the perceived need for a very short statement that would differentiate science from pseudoscience. This statement has been endorsed as a proposal to other scientific societies by the Council of the American Physical Society, and was endorsed by the Executive Board of the American Association of Physics Teachers in 1999:

Science is the systematic enterprise of gathering knowledge about the world and organizing and condensing that knowledge into testable laws and theories. The success and credibility of science is anchored in the willingness of scientists to:

1. Expose their ideas and results to independent testing and replication by other scientists; this requires the complete and open exchange of data, procedures, and materials;



The Trapezium, the star cluster in the middle of the Orion Nebula, imaged with the Hubble Space Telescope.



An artist's conception of the James Webb Space Telescope, as it will be built by Northrop Grumman for launch in 2010.

2. Abandon or modify accepted conclusions when confronted with more complete or reliable experimental evidence. Adherence to these principles provides a mechanism for self-correction that is the foundation of the credibility of science.

Our book, through the methods it describes, should reveal this systematic enterprise of science to the readers.

This book was conceived and written specifically as a *short* book for the one-semester or one-quarter introductory astronomy course. It is not a condensation of Pasachoff's *Astronomy: From the Earth to the Universe*, though obviously some of the narrative and visual content derive from that book. Some instructors professed a desire to teach from a shorter text than the usual "standard" introductory book, and *The Cosmos: Astronomy in the New Millennium* is the result of those requests. Because one cannot adequately cover the whole Universe in a few months, we have therefore had to pick and choose topics from within the various branches of astronomy, while trying to describe a wide range, to convey the spirit of contemporary astronomy and of the scientists working in it. Our mix includes much basic astronomy and many of the exciting topics now at the forefront.

## **ORGANIZATION**

The Cosmos: Astronomy in the New Millennium is organized in an Earth-outward approach. Chapter 1 gives an overview of the Universe. Chapters 2, 3, and 4 present, respectively, fundamental astronomical concepts about light, matter, and energy; the various types of telescopes used to explore the electromagnetic spectrum; and a discussion of easily observed astronomical phenomena and the celestial sphere.

Chapter 5 examines the early history of the study of astronomy. Chapters 6 through 8 cover the Solar System and its occupants, although an in-depth discussion of the Sun is reserved for later, in Chapter 10. Chapter 6 compares Earth to the Moon and Earth's nearest planetary neighbors, Venus and Mars. Based largely on the Voyager data, Chapter 7 compares and contrasts the Jovian gas/liquid giants—Jupiter, Saturn, Uranus, and Neptune. Chapter 8 looks at the outermost part of the Solar System, including Pluto and its moon, Charon. Chapter 8 also spotlights comets and meteoroids, the Solar System's vagabonds. Chapter 9, new to this edition, discusses the formation of our own Solar System and describes the exciting discoveries of over 100 planets around other stars.

Chapter 10 discusses the Sun, our nearest star. Moving outward, Chapters 11 through 14 discuss all aspects of stars. Chapter 11 begins by presenting observational traits of stars—their colors and types—and goes on to show how we measure their distances, brightnesses, and motions. It also discusses binary stars, variable stars, and star clusters, in the process showing how we derive stellar masses and ages. Chapter 12 answers the question of how stars shine and reveals that all stars have life cycles. Chapter 13 tells what happens when stars die and describes some of the peculiar objects that violent stellar death can create, including neutron stars and pulsars. Black holes, the most bizarre objects to result from star death, are the focus of Chapter 14.

As we explore further, Chapter 15 describes the parts of the Milky Way and our place in it. Chapter 16 pushes beyond the Milky Way to discuss galaxies in general, the fundamental units of the Universe, and evidence that they consist largely of dark matter. Ways in which we are studying the evolution of galaxies are also described. Chapter 17 looks at quasars, distant and powerful objects that are probably gigantic black holes swallowing gas in the central regions of galaxies. Chapters 18 and 19 consider the ultimate questions of cosmological creation

by analyzing recent findings and current theories. Evidence for an accelerating expansion of the Universe, possibilities for the overall geometry and fate of the Universe, ripples in the cosmic background radiation, the origin and phenomenally rapid early growth of the Universe, and the idea of multiple universes are among the fascinating (and sometimes very speculative) topics explored. Lastly, Chapter 20 discusses the always-intriguing search for extraterrestrial intelligence.

# **FEATURES**

The Cosmos: Astronomy in the New Millennium offers instructors a short text with concise coverage over a wide range of astronomical topics. An early discussion of the scientific method stresses its importance in the verification of observations. The text presents up-to-date coverage of many important findings and theories as well as the latest images, including observations of Jupiter and Saturn from the Cassini mission, close-up observations of Mars, images from the landing on Eros of the Near Earth Asteroid Rendezvous (NEAR Shoemaker) spacecraft, infrared images of stars in formation and of gas near them, and coverage of the 2002 total solar eclipse. We provide, as well, a sampling of the many significant findings from the Hubble Space Telescope, including some from the Advanced Camera for Surveys that was installed in 2002 and the infrared imager that was rejuvenated at the same time. Many images from the Chandra X-ray Observatory also appear. Of particular interest is the recent advance in our understanding of the age and expansion of the Universe, both through better measurements of the current expansion rate and through discussion of the conclusion that the Universe's expansion may be speeding up with time. We also discuss the very recent, exciting measurements that allow astronomers to determine the overall geometry of the Universe and the long-ago origin of its structure through detailed observations of the cosmic background radiation.

# **ORIGINS**

The study of our origins, whether it be ourselves as humans, our Earth as a planet, our Sun as a star, or our galaxy as a whole, is as interesting to many of us as it is to look at our own baby pictures. Most of us have gazed at the stars and wondered how they came to be and what their relationship to us is. NASA has chosen *Origins* as one of its major themes for the organization of its missions and has several spacecraft planned in the Origins program discussed later in Chapter 1. We emphasize the study of origins in this text, first by singling out specifics in the headings of each chapter and then by dealing with a variety of relevant material in the text itself.

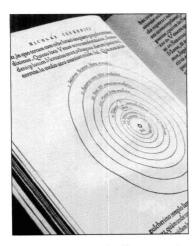
# **PEDAGOGY**

Mixed in the book we have five kinds of features:

- 1. People in Astronomy. Each of these interviews presents a notable contemporary astronomer engaged in conversation about a variety of topics: current and future work in astronomy, what led that person to study and pursue astronomy as a career, and why learning about astronomy is an important scientific and human endeavor. We hope that you enjoy reading their comments as much as we enjoyed speaking with them and learning about their varied interests and backgrounds.
- **2.** Starparties. An occasional feature that shows students how to find things in the sky. These include observing exercises and links to the star maps that appear on the inside covers of the book.



A close-up of Mars from Mars Global Surveyor. We see gullies on the walls of a meteorite impact crater that occurs in Newton Basin in Sirenum Terra.



The first heliocentric diagram published, in Copernicus's 1543 *De Revolutionibus*.

- 3. Figure It Out. In some astronomy courses it may be appropriate to elaborate on equations. Because we wrote The Cosmos: Astronomy in the New Millennium to be a descriptive presentation of modern astronomy for liberal arts students, the use of mathematics has been kept to a minimum. However, we recognize that some instructors wish to introduce their students to more of the mathematics associated with astronomical phenomena. Consequently, several additional features of this kind appear, compared with the set of such features in this book's first edition.
- **4.** *Lives in Science.* These boxes provide biographies of important historical figures like Copernicus and Galileo.
- **5.** A Closer Look. Using these boxes, students can further explore interesting topics, such as size scales in the Universe, observing with large telescopes, various celestial phenomena, mythology, and naming systems.

We have provided aids to make the book easy to read and to study from. New vocabulary is boldfaced in the text, and in the summaries that are given in context at the end of each chapter, and defined in the glossary. The index provides further aid in finding explanations. End-of-chapter questions cover a range of material and include some that are straightforward to answer from the text and others that require more thought. Appendices provide some standard and recent information on planets, stars, constellations, and nonstellar objects. The exceptionally beautiful Sky Maps by Wil Tirion (inside the cover of the book) will help you find your way around the sky when you go outside to observe the stars. Be sure you do.

Recent educational research has shown that students often need to unlearn incorrect ideas in order to understand the correct ones. We have thus placed a list of such "Misconceptions," including common incorrect ideas and the correct alternatives, on the book's Web site. Topics where these misconceptions commonly arise are marked in the book itself with an icon.

CD-ROMs have become so commonplace that we are glad to integrate their use into our text. The CD-ROM *TheSky*<sup>®</sup>, with its planetarium software, comes with the book. Another CD-ROM, *RedShift*<sup>®</sup> *College Edition (RSCE)*, has interesting animations on many topics covered in the text in addition to planetarium software and is available as a package shrink-wrapped with the book. Many relevant URLs from the World Wide Web are also listed in this book's Web site and are called out with icons in the text.

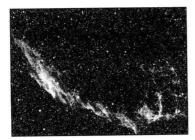
This book's Web page (http://info.brookscole.com/pasachoff) is updated frequently with links to information and photographs from a wide variety of sources and also is denoted with an icon. A section for students includes multiple-choice self-tests and other useful information. A section for professors, for which a password is required, provides various teaching aids, including most of this book's images. Both professors and students have access to news updates and new Web links. Updates appear at this book's other Web site at http://www.solarcorona.net a little earlier than they appear on the Brooks/Cole version of the Web site. Each professor and each student should frequently look at these updates and links, which are organized in chapter order. Thus the updates should be checked for each lecture and each chapter read.

# **ANCILLARY MATERIALS**

Available to those who adopt this book are the following ancillaries:

Instructor's Manual and Test Bank. This manual contains course outlines, answers to all the questions in the text, lists of audiovisual aids and organizations,





The Veil Nebula, part of the Cygnus Loop supernova remnant.

laboratory experiments and exercises arranged for easy duplication, and sample tests with answers (quizzes and exams). The test bank portion contains approximately 1250 questions in multiple-choice and other formats.

*Overhead Transparencies.* This set contains color overhead transparencies of many of the text's images.

Computerized Test Bank. All the questions from the printed test bank are presented in a computerized format that allows instructors to edit, add questions, and print assorted versions of the same test. Available for Windows® and Macintosh® users.

*Instructor's Photo Resource Catalog.* Many of the text's images are provided in an electronic file format for use in classroom presentations. This catalog is available both on a CD-ROM and as a downloadable Web file.

Multimedia Manager, WebTutor™, and MyCourse 2.0. Tools to help professors use Microsoft® PowerPoint®, WebCT, and Blackboard or to build Web sites. TheSky. This CD-ROM, from Software Bisque, is supplied with each copy of the text. It provides a planetarium-type program that allows you to demonstrate the sky in different directions and at different times. TheSky's tutorial, "Patterns in TheSky," includes definitions and many illustrations. A Workbook is also available.

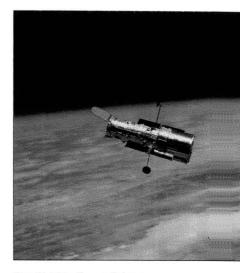
RedShift College Edition. This CD-ROM (available to students shrink-wrapped with the text as a kit whose ISBNs are available through the Web site at http://www.solarcorona.net) is a special version of the powerful RedShift software from Maris Multimedia. RedShift allows you to duplicate the look of the celestial sphere on your computer, to watch animated essays on various astronomical topics, to examine several astronomical phenomena, or to see the special features provided to accompany this text. A Workbook is also available; it provides home exercises or labs using RedShift to elucidate a variety of topics.

These items are available to qualified adopters. Please consult your local sales representative for details. For more information about these ancillaries, visit http://info.brookscole.com or contact your local Brooks/Cole sales representative by e-mail at info@brookscole.com, by calling 800-423-0563, or by faxing 859-647-5020. See http://info.brookscole.com/pasachoff for forms to order instructors' sample copies.

## **ACKNOWLEDGMENTS**

The publishers join us in placing a heavy premium on accuracy, and we have made certain that the manuscript has been read not only by students for clarity and style but also by other professional astronomers for scientific comments. As a result, you will find that the statements in this book, brief as they are, are authoritative.

This second edition benefited from the advice of reviewers Gibor Basri (University of California, Berkeley), Orville Day (East Carolina University), John Eggert (Daytona Beach Community College), Thomas Hockey (University of Northern Iowa), Roger Kadala (Hawaii Pacific University), Robert Kren (University of Michigan, Flint), Claud Lacy (University of Arkansas), Philip Lockett (Centre College), John Mattox (Francis Marion University), and Charles Rogers (Southwestern Oklahoma State University). We thank Kelly Beatty (Sky & Telescope) and Heidi Hammel (Southwest Research Institute) for their comments on Solar-System material. Additional suggestions were provided by Joshua Winn (Harvard-Smithsonian Center for Astrophysics) and Geoff Marcy (University of California, Berkeley). We also found useful the extensive comments



The Hubble Space Telescope, during its 2002 repair mission.



The center of the Trifid Nebula, from the 8-m Gillett Gemini Telescope.

on a questionnaire filled out by A.F.'s students at UC Berkeley and past comments from J.M.P.'s students at Williams.

We thank the following reviewers for their help with the first edition of *The Cosmos*: Phillip Appleton (Iowa State University), Kelly Beatty (*Sky & Telescope* magazine), Robert Egler (North Carolina State University), Thomas Hockey (University of Northern Iowa), Scott Payson (Wayne State University), Steinn Sigurdsson (Pennsylvania State University), and Dan Wilkins (University of Nebraska, Omaha). A number of instructors alerted us to typos and minor errors.

We would also like to thank John Dykla (Loyola University), Hollis R. Johnson (Indiana University), Steven L. Kipp (Mankato State University), John P. Oliver (University of Florida), James G. Peters (San Francisco State University), Harley A. Thronson (University of Wyoming), and Louis Winkler (Pennsylvania State University), who commented on *Journey Through the Universe*, which served as a base on which this book was rewritten. We thank, further, John Martin (San Jose City College), as well as David Tholen (University of Hawaii) and Richard Canfield (then at the University of Hawaii and now at Montana State University) and their students, for their post-publication comments on *Journey*.

J.M.P. is especially grateful to Susie Kaufman for her expert editorial work throughout this project. Linda Crowe has capably assisted with the final stages of publication. We are also grateful to Nancy Kutner for her excellent work on the index, Barbara Swanson for her general assistance, Ethan Ravetch for his valuable help with the illustration manuscript and other aspects of the second edition, and Stephan Martin and Milos Mladenovic for their computer work on illustrations and this book's Web pages.

At Brooks/Cole, we thank Keith Dodson (Acquisitions Editor), Marie Carigma-Sambilay (Development Editor), Samuel Subity (Electronic Technology Manager), and Kelley McAllister (Marketing Manager). We also thank Robin Bonner, Editorial Director at NOVA Graphic Services, the project manager for this edition and a veteran of the earlier edition.

J.M.P. thanks various members of his family, who have provided vital and valuable editorial services in addition to their general support. His wife, Naomi, has always been very helpful both personally and editorially. As adults, Eloise and Deborah Pasachoff continue to provide comments and analysis and to read proof, as they have for many years. J.M.P. welcomes Tom Glaisyer to these family duties. A.F. thanks his young children, Zoe and Simon Filippenko, and Noelle Edwards for their patience and support while this book was being written and revised.

We are extremely grateful to all the individuals named above for their assistance. Of course, it is we who have put this all together, and we alone are responsible for the content. We would appreciate hearing from readers with suggestions for improved presentation of topics, with comments about specific points that need clarification, with typographical or other errors, or just to tell us how you like your astronomy course. We invite readers to write to us, respectively, at Williams College, Hopkins Observatory, 33 Lab Campus Drive, Williamstown, MA 01267–2630, and Astronomy Department, University of California, Berkeley, CA 94720–3411, by e-mail, or through the book's Web sites. We promise a personal response to each writer.

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# Web sites

http://info.brookscole.com/pasachoff http://www.solarcorona.net

# To the Students

stronomy has much variety, and you are sure to find some parts of it that interest you more than others. Do try to get an overview from this text and then go on to do additional reading. (We give some suggestions at the end of the book.) Socrates said, "Education is the kindling of a flame, not the filling of a vessel"; it is in this spirit that we wrote this text. We hope you will continue to learn more about our origins and place in the Cosmos.

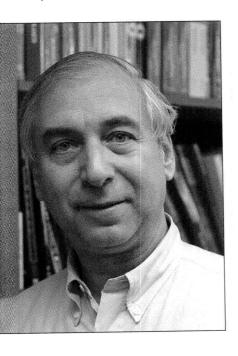
To get the most out of this text, you must read each chapter more than once. After you read each chapter the first time, you should carefully go through the summary, trying to understand each of the key concepts and the necessary vocabulary. You can look up boldfaced words in the glossary (or in the dictionary of the *RedShift College Edition CD-ROM*) and also find the definition that appears with the word the first time it is used in the chapter; the index will help you find these references. Next, read through the chapter again especially carefully. Studying the illustrations and captions will also provide you with further explanations of much of the material presented. Finally, answer the questions at the end of the chapter. Make sure that the common misconceptions listed on the Web site aren't ones that you share.

We hope these steps help you understand the Universe we live in, the things in it, and how astronomers find out about them.



The spiral galaxy M74, from the 8-m Gillett Gemini Telescope.

# About the Authors



ay M. Pasachoff is Field Memorial Professor of Astronomy at Williams College, where he teaches the astronomy survey course and works with undergraduate students on a variety of astronomical projects. He is also Director of the Hopkins Observatory there.

Pasachoff has taken advantage of his broad experience with a wide variety of ground-based telescopes and spacecraft in writing his texts. Pasachoff received

the 2003 Education Prize of the American Astronomical Society.

Pasachoff's expedition, with a dozen students, to the 2002 total solar eclipse was his 35th solar eclipse. His research has been sponsored by the National Science Foundation, NASA, and the National Geographic Society. He is Chair of the Working Group on Eclipses of the International Astronomical Union and of a Program Group on Public Education at the Times of Solar Eclipses. He is a collaborator with a group of scientists observing the atmospheres of outer planets and their moons, including Pluto and Neptune's moon Triton. He also works in radio astronomy of the interstellar medium, concentrating on deuterium and its cosmological implications. He has recently been collaborating with a professor of art history on astronomical images in the art of Renaissance Italy and of Great Britain.

Pasachoff has been very active in educational and curriculum matters. He is U.S. National Liaison to and President (2003–2006) of the Commission on Education and Development of the International Astronomical Union, has twice been Chair of the Astronomy Division of the American Association for the Advancement of Science, and has been on the astronomy committees of the American Astronomical Society, the American Physical Society, and the American Association of Physics Teachers. He is on the Council of Advisors of the Astronomy Education Review. He has spearheaded a discussion of what should be taught in astronomy courses, championing the position of including contemporary astronomy. He is a Fellow of the American Physical Society, the International Planetarium Society, and the Royal Astronomical Society, and has held a Getty Fellowship. He has lectured widely, including a stint as a Sigma Xi Distinguished Lecturer.

In addition to his college astronomy texts, Pasachoff has written the Peterson Field Guide to the Stars and Planets, and is author or coauthor of textbooks in calculus and in physics, as well as several junior-high-school textbooks. His continued dedication to teaching astronomy through interesting, up-to-date, and accurate textbooks is a hallmark of his work. He collaborated on a trade book: Nearest Star: The Exciting Science of Our Sun. A list of his books is available at http://www.solarcorona.com.

Pasachoff received his undergraduate and graduate degrees from Harvard and was at Caltech before going to Williams College. His sabbaticals and other leaves have been at the University of Hawaii's Institute for Astronomy, the Institute d'Astrophysique in Paris, the Institute for Advanced Study in Princeton, and the Harvard-Smithsonian Center for Astrophysics.

lex Filippenko is a Professor of Astronomy at the University of California, Berkeley. After receiving his bachelor's degree in Physics from the University of California, Santa Barbara (1979), and his doctorate in Astronomy from the California Institute of Technology (1984), he went to the University of California, Berkeley as a postdoctoral fellow, and in 1986 he joined the Berkeley faculty. He is an active member of the International Astronomical Union, has served as Councilor of the American Astronomical Society, and was President of the Astronomical Society of the Pacific from 2001 to 2003.

Filippenko's primary areas of research are supernovae (exploding stars), active galaxies, black holes, and cosmology; he has also spearheaded efforts to develop completely robotic telescopes. He and his collaborators recognized a new class of exploding star, obtained some of the best evidence for the existence of stellar-mass black holes in our Milky Way Galaxy, and found that other galaxies commonly show vigorous activity in their centers that suggests the presence of supermassive black holes. His robotic telescope at Lick Observatory is conducting the world's most successful search for exploding stars in relatively nearby galaxies, having found hundreds of them. He also made major contributions to the discovery that the expansion rate of the Universe is speeding up with time, propelled by a mysterious form of "dark energy"—the top "Science Breakthrough of 1998," according to the editors of *Science* magazine.

Filippenko's research accomplishments, documented in over 400 published scientific papers, have been recognized with several major awards, including the Newton Lacy Pierce Prize of the American Astronomical Society (1992) and the Robert M. Petrie Prize of the Canadian Astronomical Society (1997). A Fellow of the California Academy of Sciences (elected 1999), he has also been a Guggenheim Foundation Fellow (2001), a Phi Beta Kappa Visiting Scholar (2002), and a distinguished visiting lecturer at numerous colleges and universities.

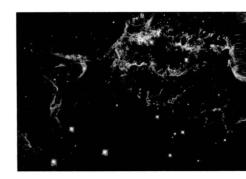
Filippenko has always been strongly motivated to communicate science to the general public in a clear, enthusiastic, and engaging manner. In 1991 he won the two most coveted teaching awards at Berkeley, each of which is generally given only once per career, and in 1995 and 2001 he was voted "Best Professor" on campus in informal student polls. He frequently gives public lectures on astronomy, and he has played a prominent role in science newscasts and television documentaries such as "Mysteries of Deep Space," "Stephen Hawking's Universe," and "Runaway Universe." In 1998, working with The Teaching Company, he produced a 40-lecture video course on basic college-level astronomy ("Understanding the Universe: An Introduction to Astronomy"), and in 2003 he produced a 16-lecture update to this course.





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The supernova remnant Cassiopeia A. Sulfur shows as red and oxygen as blue in this Hubble image.

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The galaxy ESO 510-G13 with its warped disk.



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The Mauna Kea Observatory in Hawaii, with the Subaru and Keck telescopes at the center, the "Millimeter Valley" at the left, and the Infrared Telescope Facility at the right.

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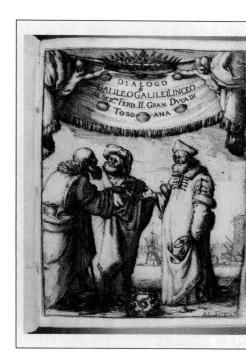
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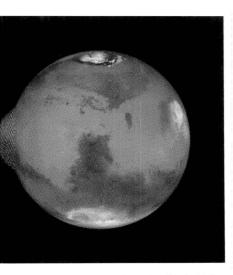
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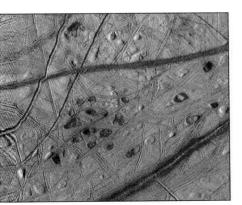
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