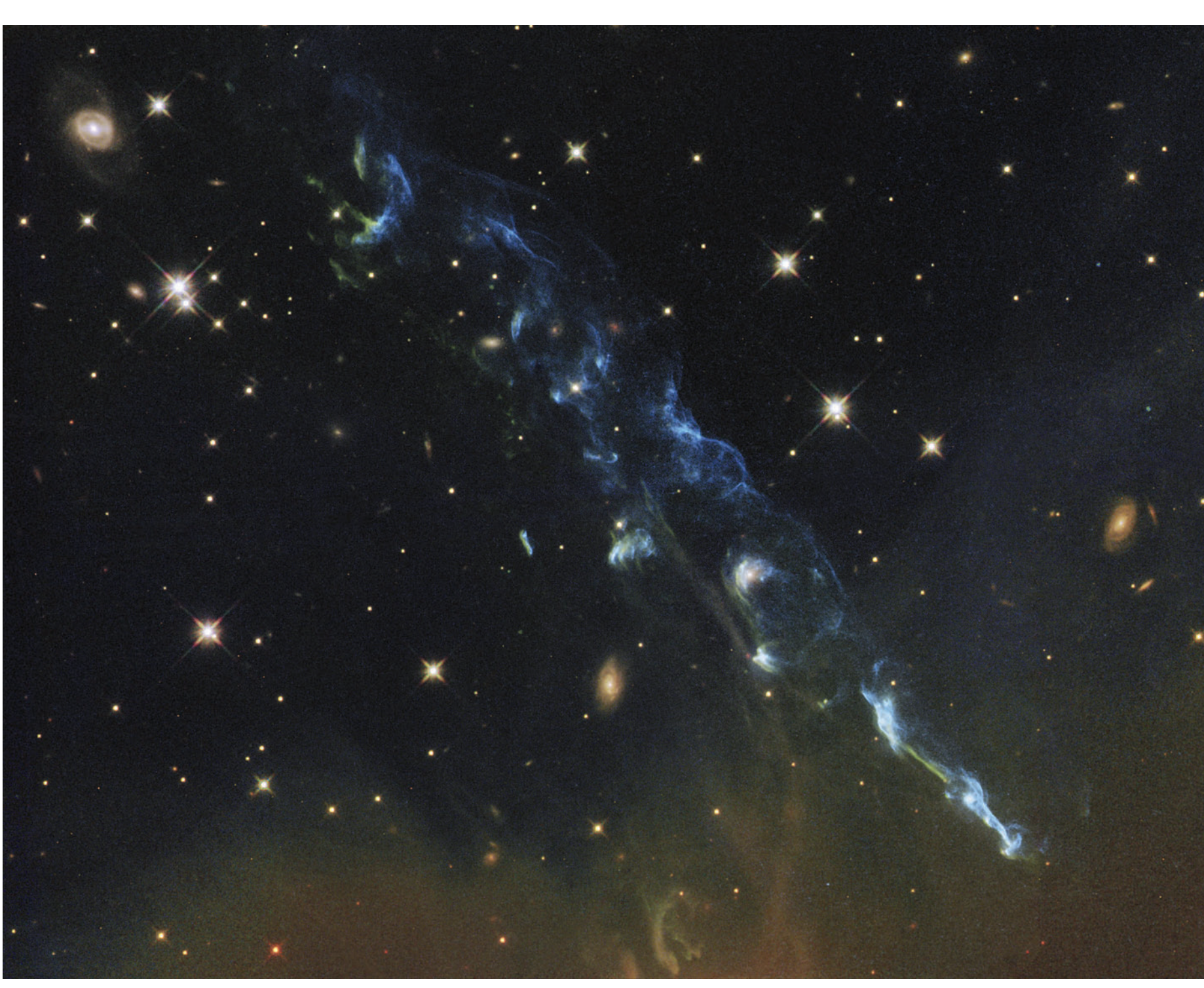

NASA, ESA, and the Hubble Heritage Team (STScI/AURA)

A geyser of hot gas, known as Herbig-Haro 110, from a newborn star ricochets from the core of a cloud of hydrogen molecules; a combination of images taken with the Hubble Space Telescope.

THE COSMOS

Fourth Edition

An exciting introduction to astronomy, the fourth edition of this book uses recent discoveries and stunning photography to inspire non-science majors about the Universe and science. Written by two highly experienced and engaging instructors, each chapter has been fully updated, with more than 200 new images throughout, including recent images from space missions and the world's best observatories. Redesigned, streamlined pages highlight the breathtaking imagery.

The text is organized as a series of stories, each presenting the history of the field, the observations made and how they fit within the process of science, our current understanding, and what future observations are planned. Math is provided in boxes and easily read around, making the book suitable for courses taking either mathematical or qualitative approaches. New discussion questions encourage students to think widely about astronomy and the role science plays in our everyday lives, and podcasts for each chapter aid studying and comprehension. Tables, Appendices, Selected Readings, and the Glossary have all been updated.

Jay 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 research projects. He is also Director of the Hopkins Observatory there. He received his undergraduate and graduate degrees from Harvard and was at the California Institute of Technology, where he has also had recent sabbatical leaves, before going to Williams College.

Pasachoff pioneered the emphasis in textbooks on contemporary astronomy alongside the traditional bases. He has taken advantage of his broad experience with a wide variety of ground-based telescopes and spacecraft in writing his texts. Also, "For his eloquent and informative writing of textbooks…, For his devotion to teaching generations of students, For sharing with the world the joys of observing eclipses, For his many popular books and articles on astronomy, For his intense advocacy on behalf of science education in various forums, For his willingness to go into educational nooks where no astronomer has gone before," he received the American Astronomical Society's 2003 Education Prize.

Pasachoff's expedition with students to the 2012 total solar eclipse was his 56th solar eclipse. He has also been carrying out research on transits of Venus and of Mercury. His research has recently been sponsored by the National Science Foundation, NASA, and the National Geographic Society. He is Chair of the Working Group on Eclipses of the solar division of the International Astronomical Union and Chair of the American Astronomical Society's Historical Astronomy Division. He is collaborating with colleagues to observe occultations of stars by Pluto, its largest moon (Charon), and other objects in the outer parts of the Solar System. He also works in radio astronomy of the solar atmosphere and of the interstellar medium, concentrating on deuterium and its cosmological consequences.

Pasachoff has been President of the Commission on Education and Development of the International Astronomical Union and twice Chair of the Astronomy Division of the American Association for the Advancement of Science. He is co-editor of *Teaching and Learning Astronomy: Effective Strategies for Educators Worldwide* (2005) and of *Innovation in Astronomy Education* (2008). Asteroid (5100) Pasachoff is named for him.

Alex Filippenko is a Professor of Astronomy and the Richard & Rhoda Goldman Distinguished Professor in the Physical Sciences at the University of California, Berkeley. His teaching of an astronomy survey course is very popular on campus; he has won the most coveted teaching awards at Berkeley and has nine times been voted "Best Professor" on campus. In 2006, he was named the U.S. National Professor of the Year. In 2010, he won the Emmons Award of the Astronomical Society of the Pacific for excellence in college astronomy teaching. He received his undergraduate degree from the University of California, Santa Barbara, and his doctorate from the California Institute of Technology.

Filippenko has produced five video courses on college-level astronomy through *The Great Courses*. The recipient of the 2004 Carl Sagan Prize for Science Popularization, he lectures widely, and he has appeared frequently on science newscasts and television documentaries, especially *The Universe* series on The History Channel and H2 (about 40 episodes spanning 6 seasons).

Filippenko's primary areas of observational research are exploding stars (supernovae), gamma-ray bursts, active galaxies, black holes, and observational cosmology; he frequently uses the Hubble Space Telescope, the Keck 10-meter telescopes, and other facilities. He and his collaborators have obtained some of the best evidence for the existence of stellar-mass black holes in our Milky Way Galaxy. His robotic telescope at Lick Observatory, together with a large team that includes many undergraduate students, is conducting one of the world's most successful searches for exploding stars in relatively nearby galaxies, having found more than 1,000 of them. He made major contributions to both of the teams that discovered the accelerating expansion of the Universe, and the team leaders received the 2011 Nobel Prize in Physics for their work. One of the world's most highly cited astronomers, his research has been recognized with several prestigious awards, including election to the U.S. National Academy of Sciences.

He has served as a Councilor of the American Astronomical Society and has been Vice President and President of the Astronomical Society of the Pacific. He is an active member of the International Astronomical Union.

"This is an extraordinarily attractive, captivating, and easy-to-follow textbook of modern astronomy. I will happily continue to use it in teaching my course."
Professor Alex Wolszczan, Penn State University

"… the work of two great astronomers and top teachers … clear and concise. This is the text I would use for my introductory astronomy course."
Professor Arun Venkatachar, Ohio University

"The authors convey a clear and enthusiastic pedagogic presentation of an exciting field. As a textbook, it will be of great benefit to students, providing a valuable starting point to learn about the subject … *The Cosmos* stands out for its continued excellence over time."
Dr. Roger Kadala, Hawaii Pacific University

"… long considered one of the best descriptive astronomy books, the new Fourth Edition is even better … not only a beautifully illustrated text, but has many of the latest developments in astronomy."
Professor Victor Kriss, Lewis-Clark State College

"… my first choice for a textbook for introductory astronomy. Hundreds of students in my introductory astronomy class have used *The Cosmos* as the primary text, and I am very happy with the coverage and presentation of the material."
Professor Steinn Sigurðsson, Penn State University

"… a splendid new addition to *The Cosmos* series, distinguished by its crisp, interesting, and informative style and made all the more accessible through the generous use of photographs, charts, and diagrams that greatly facilitate one's understanding."
Mark Rader, Notre Dame High School

THE COSMOS

Astronomy in the New Millennium

Fourth Edition

Jay M. Pasachoff
Williams College, Massachusetts

Alex Filippenko
University of California, Berkeley

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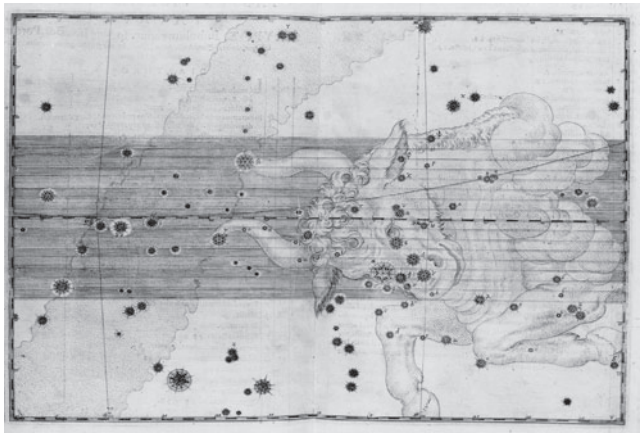
BRIEF CONTENTS



Jay M. Pasachoff collection

The constellation Taurus, the Bull, from the 1603 star atlas by Johann Bayer.

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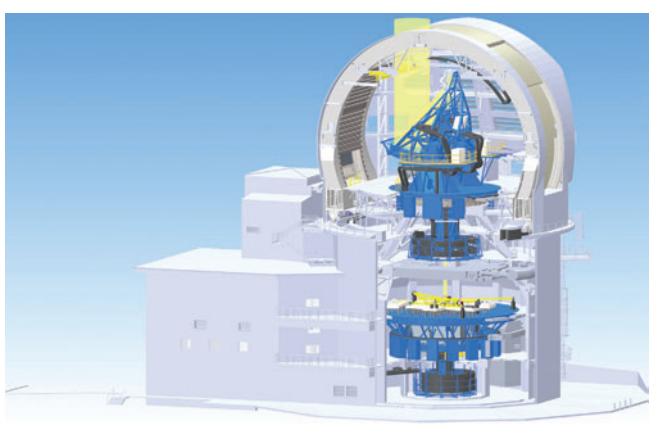
NASA, ESA, and E. Sabbi (ESA/STScI)/R. O'Connell (University of Virginia) and the Wide Field Camera 3 Science Oversight Committee

Merging star clusters in 30 Doradus, in the Large Magellanic Cloud, imaged with the Hubble Space Telescope.



ATST/NSO/NSF, image by L. Phelps

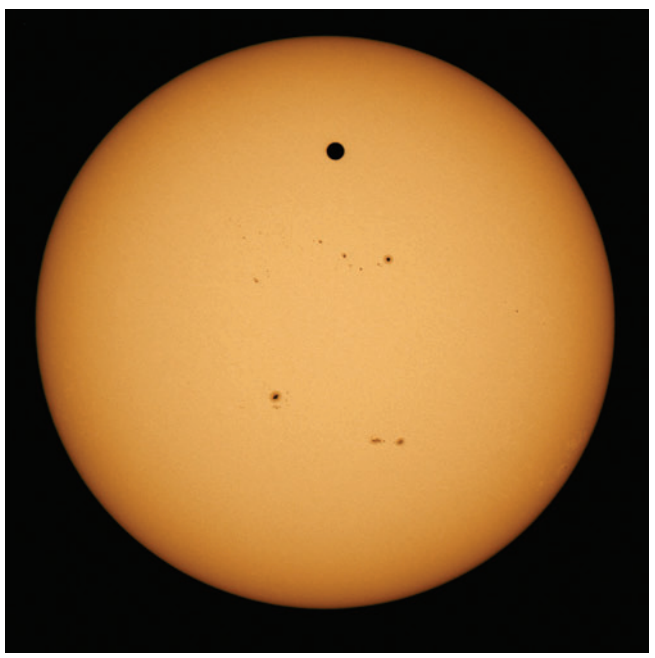
An artist's rendering of the Advanced Technology Solar Telescope with its 4-m-diameter mirror, now being erected on Haleakala, Maui, Hawaii.

Jay M. Pasachoff collection

The frontispiece of Galileo's *Dialogo*, published in 1632.

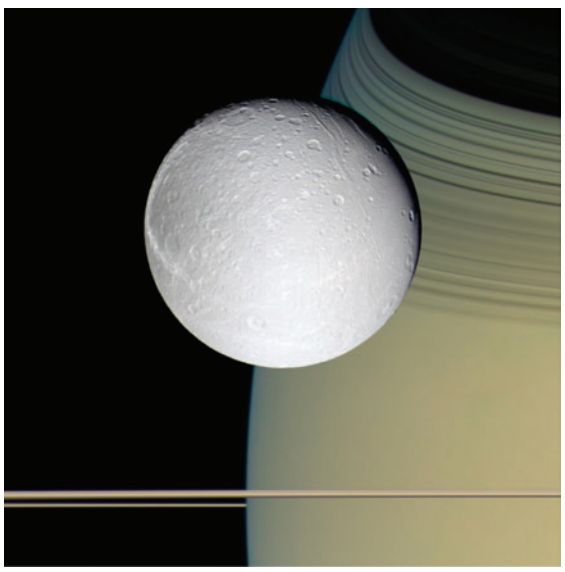
NASA/JPL-Caltech/Malin Space Science Systems

A self-portrait mosaic image of Curiosity, the lander of NASA's Mars Science Laboratory, with Gale Crater's Mount Sharp at background right.



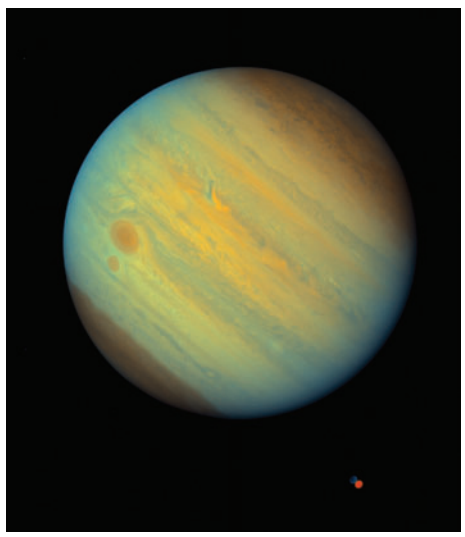
Ronald Dantowitz (Clay Center Observatory) and Jay M. Pasachoff (Williams College)/National Geographic Society Committee for Research and Exploration

Venus's silhouette shows, as do sunspots, in the middle of the six-hour transit of Venus across the face of the Sun on June 5/6, 2012.



NASA/JPL/Space Science Institute

Saturn's moon Titan in front of the planet and its rings, from NASA's Cassini spacecraft in 2012.



Jay M. Pasachoff, Glenn Schneider, and colleagues/STScI/NASA/ESA

Jupiter with the Hubble Space Telescope, a composite of an ultraviolet and an infrared image made as part of one of the authors' observations made in 2012 while a transit of Venus as seen from Jupiter was dimming that giant planet by 0.01%.

Jay M. Pasachoff/Williams College Eclipse Expedition/NSF

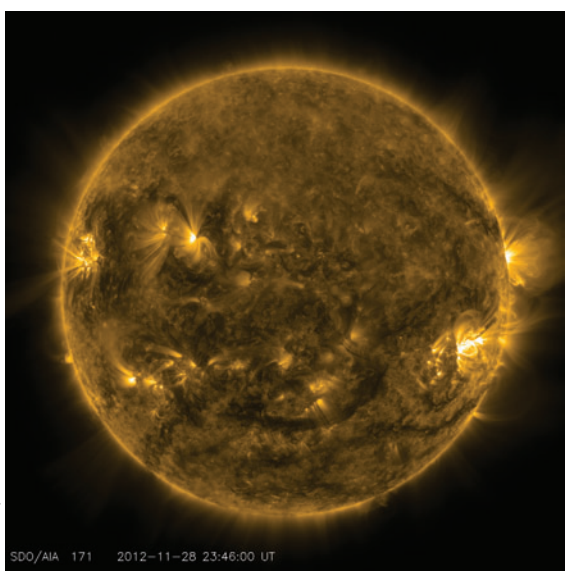
The shadow of the Moon surrounds the eclipsed Sun in this view from a helicopter, above an Australian cloud-deck, of the 2012 total solar eclipse; we see the solar corona surrounding the dark silhouette of the Moon.

NASA/JPL-Caltech/UCAL/MPS/DLR/IDA

The asteroid (4) Vesta, a mosaic of the highest-resolution images from NASA's Dawn spacecraft, which is now en route to (1) Ceres.

Jay M. Pasachoff/NSF

The diamond ring effect along with reddish chromosphere and prominences mark the end of the 2012 total solar eclipse observed from Australia.



Solar Dynamics Observatory's Atmospheric Imaging Assembly/LMSAL/NASA

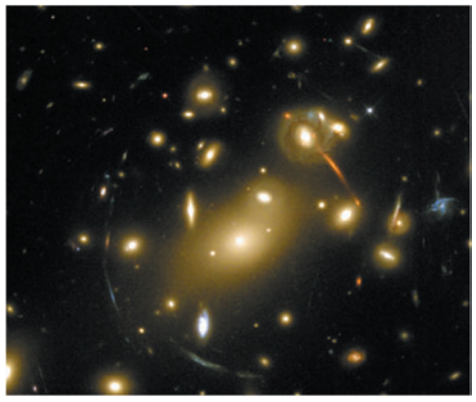
A view of the Sun in the extreme ultraviolet part of the spectrum, showing million-degree gas held in place by the solar magnetic field.

NASA, ESA, CXC, SAO, the Hubble Heritage Team (STScI/AURA), and J. Hughes (Rutgers University)

An optical and x-ray composite image of a supernova remnant, incorporating Hubble Space Telescope images showing the pink optical shell surrounding the x-ray images, shown in blue and green, from the Chandra X-ray Observatory. The supernova came from a supergiant star that exploded (Type Ia) 400 years ago in the Large Magellanic Cloud. The bubble is 23 light-years across.

NASA, ESA, the Hubble Heritage Team (STScI/AURA) – ESA/Hubble Collaboration, and W. Keel (University of Alabama)

NGC 3314, a chance alignment of two distant galaxies, imaged with the Hubble Space Telescope. The galaxies are actually separated by a distance ten times that of our galaxy from the Andromeda galaxy and are about 140 million light-years from us.



NASA, ESA, M. Postman (STScI), and the CLASH Team

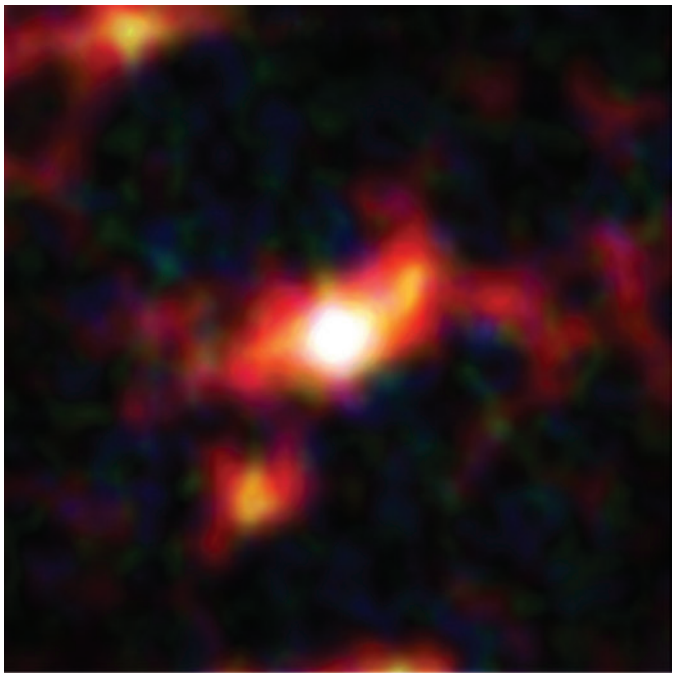
A cluster of galaxies 4.5 billion light-years away, in a Hubble Space Telescope survey that is mapping dark matter.

NASA, ESA, G. Illingworth, D. Magee, and P. Oesch (University of California, Santa Cruz), R. Bouwens (Leiden University), and the HUDF09 Team

The Hubble Space Telescope's eXtreme Deep Field (XDF), a small patch of sky at the center of the Hubble Ultra Deep Field assembled from 10 years of observations.

PREFACE

Astronomy continues to flourish, with huge discoveries such as the one that the Universe's expansion – which was long thought to be slowing down – is, astonishingly, accelerating. A generation of large optical telescopes has been built on mountaintops, and arrays of dozens of radio telescopes explore their part of the spectrum at high resolution. Still larger telescopes are being planned or built, including the Thirty Meter Telescope, the Giant Magellan Telescope, and the European Extremely Large Telescope, all for optical and near-infrared studies, as well as the Atacama Large Millimeter/submillimeter Array at an extremely high-altitude site for radio and far-infrared studies. The Hubble Space Telescope, updated with new cameras, sends down exciting data all the time, though we worry about its future and about a gap before the James Webb Space Telescope is launched. The latest space observatories transmit 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. Cosmology has become a mathematical, and even a statistical, science. NASA's Curiosity rover triumphantly landed on Mars, bearing instruments to investigate Mars's past habitability. Spacecraft are orbiting Mercury and Saturn; other spacecraft are en route to orbit Ceres and a comet. Another spacecraft is en route to Pluto and to objects beyond it. Moreover, new electronic instruments and computer capabilities, new space missions to Solar-System objects, and advances in computational astronomy and in theoretical work will continue to bring forth exciting results.



ESA/Herschel/PACS/Jean-François Lestrade, Observatoire de Paris, France

A debris disk around the M star (a very cool star) Gliese 581 as seen with the European Space Agency's Herschel Space Observatory at far-infrared wavelengths. The star hosts at least 4 planets, within 2 and 15 times Earth's mass. The debris disk extends from 25 to 60 au.The yellow-red objects are extragalactic, in the background.

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 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 citizens 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.

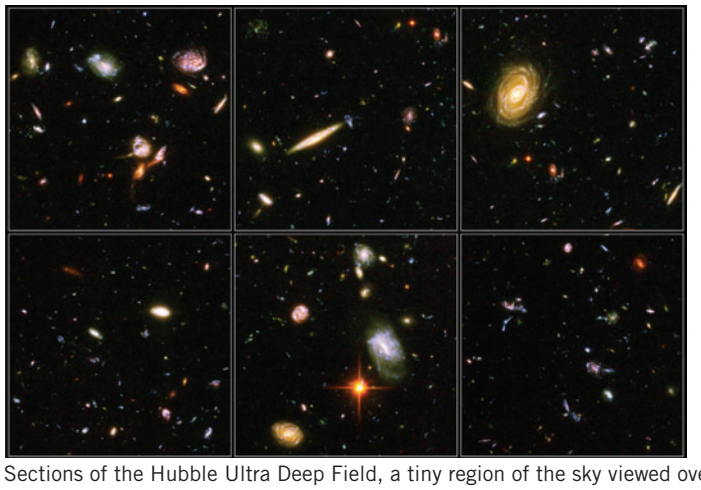
What is science? The following statement was originally drafted by the Panel on Public Affairs of the American Physical Society, in an attempt to meet the perceived need for a very short statement that would differentiate science from pseudoscience. This statement has been endorsed as a proposal to other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

> 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:

> 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;
>
> 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.

Because one cannot adequately cover the whole Universe in a few months, or even a year, we have 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.



NASA, ESA, S. Beckwith (STScI) and the HUDF Team

Sections of the Hubble Ultra Deep Field, a tiny region of the sky viewed over and over with the Hubble Space Telescope's Advanced Camera for Surveys. Many faint and distant galaxies are revealed, often interacting with each other.

ORGANIZATION

The Cosmos: Astronomy in the New Millennium is generally organized in an Earth-outward approach. Chapter 1 gives an overview of the Universe. Chapter 2 presents fundamental astronomical concepts about light, matter, and energy, while Chapter 3 summarizes the various types of telescopes used to explore the electromagnetic spectrum. In Chapter 4, we discuss easily observed astronomical phenomena and the celestial sphere. Some professors prefer to cover that material at the very beginning of the course or at other points, and there is no problem with doing so.

Chapter 5 examines the early history of the study of astronomy. Chapters 6 through 8 cover the Solar System and its occupants, although a thorough 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, Galileo, and Cassini 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, as well as other Kuiper-belt objects still farther out; the chapter also spotlights comets and meteoroids, the Solar System's vagabonds. Chapter 9 discusses the formation of our own Solar System and describes the exciting discovery of thousands of exoplanet candidates around other stars.

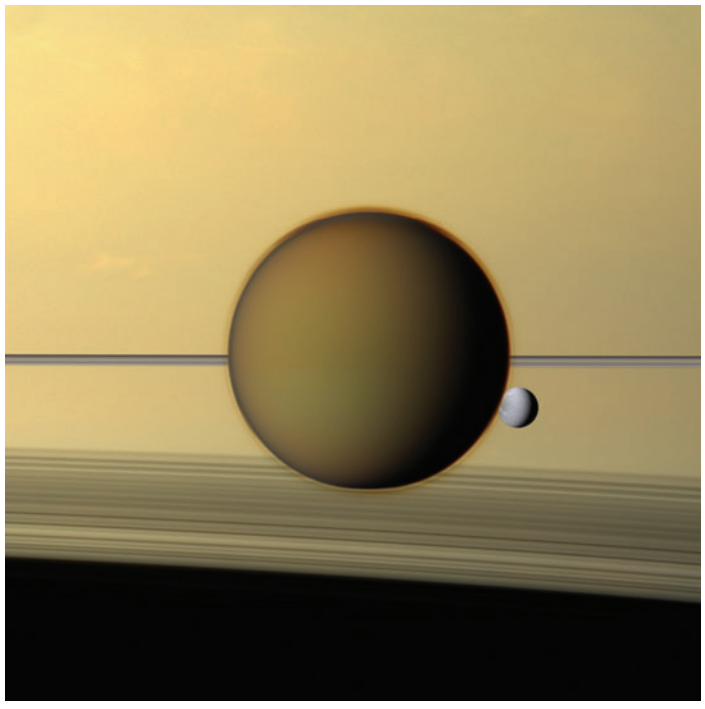
Chapter 10 concentrates on the Sun, our nearest star, exploring its various components and the solar activity cycle. Moving outward, Chapters 11 through 14 examine all aspects of stars. Chapter 11 begins by presenting observational traits of stars – their colors and types – and goes on to show how we 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 Galaxy 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 that the expansion of the Universe is currently speeding up with time (probably propelled by a mysterious "dark energy"), 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 relatively 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-Huygens mission (including the landing on Titan), close-up observations of Mars, infrared images of stars in formation and of gas near them from the largest telescope in space, and coverage of recent total solar eclipses and of the pair of transits of Venus – the like of which will not be seen on Earth until the year 2117, in the 22nd century.



NASA/JPL-Caltech/Space Science Institute

Saturn's moons Titan and, smaller, Dione through its haze, with Saturn's disk and rings in the background from NASA's Cassini spacecraft.

We provide, as well, a sampling of the many significant findings from the Hubble Space Telescope. Numerous images from the Chandra X-ray Observatory, the Spitzer Space Telescope, and the Herschel Space Observatory also appear, as do results from the Swift spacecraft that is monitoring gamma-ray bursts, among the most powerful and violent phenomena in the Universe. 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 the discovery that the Universe's expansion is currently speeding up with time. We also present the recent exciting measurements that allow astronomers to determine the overall geometry of the Universe and the early appearance of large-scale structure through detailed observations of the cosmic background radiation.

COSMIC 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 Astrophysics has chosen *Cosmic Origins* as one of its major themes for the organization of its missions and has several spacecraft planned in the Cosmic Origins program. We emphasize the study of origins in this text, dealing with a variety of relevant material. NASA Astrophysics also has two additional themes, which we also cover extensively in this text: *Physics of the Cosmos* and *Exoplanet Exploration.*

PEDAGOGY

Within the book (or, in one case, on its website) we have five kinds of features:

1. *Star Parties.* 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.
2. *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, we kept the use of mathematics to a minimum. However, we recognize that some instructors wish to introduce their students to more of the mathematics associated with astronomical phenomena. Consequently, we provide mathematical features, numbered so they can be assigned or not, at the instructor's option.
3. *Lives in Science.* These boxes provide biographies of important historical figures like Copernicus and Galileo.
4. *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 are pleased to supply some exciting close-ups of Mars, Titan, and a comet, for example.
5. *People in Astronomy.* Each of these interviews (available on the website) 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.

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 expanded 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. An expanded set of end-of-chapter questions covers a range of material and includes some that are straightforward to answer from the text and others that require more thought. Appendices provide some information on planets, stars, constellations, and nonstellar objects. The exceptionally beautiful sky maps by Wil Tirion (inside the covers of the book) will help you find your way around the sky when you go outside to observe the stars. Be sure you do.

THE COSMOS WEBSITE

Adopters of *The Cosmos*, 4th edition, have access to a rich array of teaching and learning resources at the book's web page. Students will find multiple-choice self-tests and other useful information.

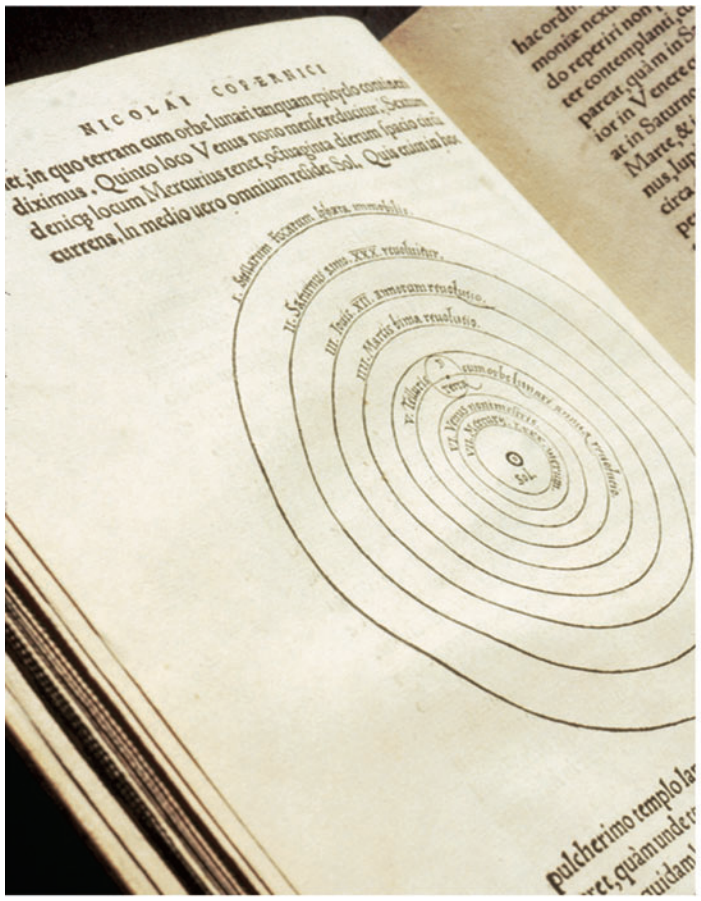
Recent educational research has shown that students often need to unlearn incorrect ideas in order to understand the correct ones. We

have thus placed a list of such "Misconceptions," including common incorrect ideas and the correct alternatives, on the book's website. The book's website also has a list of many relevant URLs from the World Wide Web.

The website is updated occasionally with links to information and photographs from a wide variety of sources. Updates also appear at this book's other website at http://www.thecosmos4.com. Each professor and each student should look at these updates and links, which are organized in chapter order.

STAR CHARTS

Pasachoff's *Peterson Field Guide to the Stars and Planets* is a suggested accompaniment for those wanting monthly star maps, star charts, and other detailed observing aids; see http://www.solarcorona.com. Quarterly star maps, improved and redrawn for this edition by the foremost celestial cartographer, Wil Tirion of The Netherlands, appear on the inside covers in *The Cosmos*, 4th edition.



Jay M. Pasachoff collection

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

ACKNOWLEDGMENTS

The publishers join us in placing a heavy premium on accuracy, and we have made certain that the manuscript and past editions have been carefully read and considered. As a result, you will find that the statements in this book, brief as they are, are authoritative.

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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, eclipse@williams.edu, and Department of Astronomy, University of California, Berkeley, CA 94720–3411, alex@astro.berkeley.edu, or through the book's websites. We promise a personal response to each writer.

A Hubble Space Telescope view of the spiral galaxy NGC 5584 with Hubble's new Wide Field Camera 3. Younger stars appear bluer and are in the spiral arms; the stars in the core are mostly older. Reddish, more distant galaxies, can be seen through the nearer galaxy, which is 72 million light years from us in the constellation Virgo. This galaxy had a Type Ia supernova, a supernova caused by the incineration of a white dwarf near its maximum mass limit. The peak apparent brightness of the supernova was measured, and its true peak power was calculated by combining this with the galaxy's distance, obtained through studies of 250 Cepheid variable stars in the galaxy. Type Ia supernovae and Cepheid variables were studied in many additional galaxies, and the calibrated supernovae were subsequently used to measure distances of large numbers of galaxies and determine the expansion rate of the Universe. This project was a main reason for the launch of the Hubble Space Telescope and for naming it after Edwin Hubble.

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