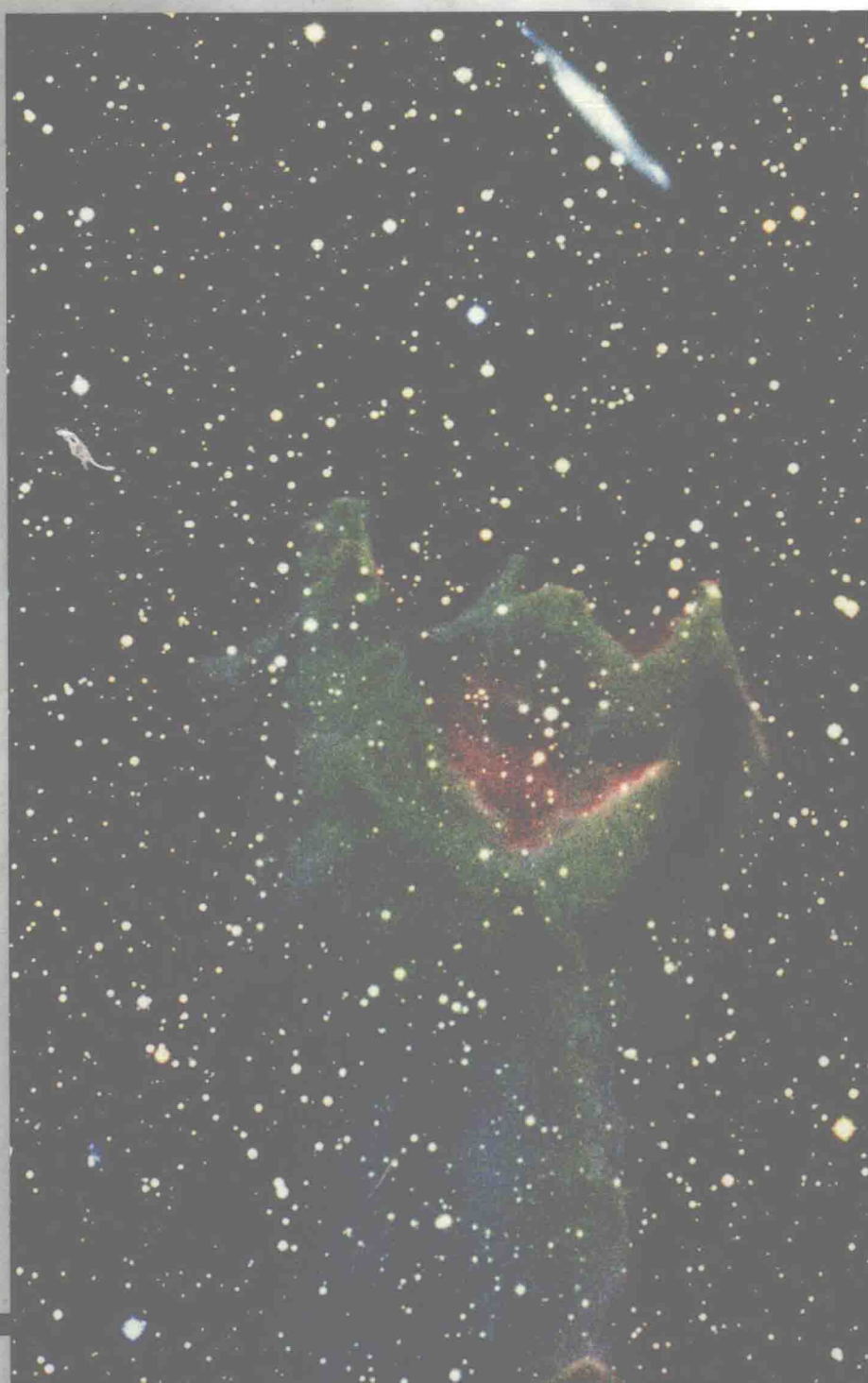
FOURTH EDITION

UNIVERSE



KAUFMANN

UNIVERSE

FOURTH EDITION

William J. Kaufmann III

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To Connie and Michael, with love

Cover image: The greenish nebula on the front cover, an interstellar cloud located about 1300 light-years from Earth, seems about to devour a spiral galaxy (seen edge-on). Radiation from the stars is eroding and elongating the nebula by blowing its gas and dust. Because of its shape, the nebula is called a *cometary globule,* but it is no comet! Its "head" alone measures about $1\frac{1}{2}$ light-years across.

Cometary globules are normally dim—because they shine primarily by reflecting light from nearby stars—and most are bluish. This nebula, however, has a muddy greenish hue because the reflected starlight reaches us only after it has filtered through a dusty cloud. The fine dust scatters and loses blue light, which has short wavelengths, more efficiently than longer wavelengths.

This remarkable photograph was taken by David Malin using the 3.9-meter Anglo-Australian Telescope. Many of his fine pictures grace the pages of this text.

Illustration credits are listed on pages 611–613.

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PREFACE

I wrote this book for the student about to explore the mysteries of the universe, from the Earth around us to the dim and distant reaches of the heavens. Armed with the powers of observation, the laws of physics, and the resourcefulness of the human mind, astronomers survey alien worlds and follow the life cycles of stars. With our growing understanding of the evolution of the universe, even space and time take on new meanings. From its first edition, *Universe* has therefore been designed to guide students, including students who may be less than at ease in mathematics and the physical sciences, faced with some of the most profound questions ever asked: from the creation of the cosmos to the formation of the planets and the motions of the stars.

I also wrote this book for the instructor who wants to inspire questions about the nature of any scientific inquiry—about how we ever come to know what we know. Astronomers today must investigate realms far removed from daily experience, including objects too vast, distant, or intangible ever to sample directly; many of the phenomena that we observe occurred very long ago. Showing how scientists reason is therefore central to this fourth edition.

Our developing picture of the universe guides the features of this book

Astronomy reveals the fascinating nature of our physical universe and how it is comprehended. This twin emphasis determines both the text's organization and each of its features:

- A chapter or part typically begins with questions and observations, **showing how scientists discover new physical principles.**
- A **modular part structure** allows instructors to probe these questions in the order and depth desired.
- **Optional boxes** further develop the underlying reasoning, with many ***new*** **worked examples** as a guide to the calculations.
- The **many color illustrations**—from *newly obtained* photographs to ***new*** **supercomputer simulations**—are carefully coordinated with the text to make the observations essential to astronomy vivid and easy to understand.
- **Frequent highlighting** and an ***added*** **range of end-of-chapter questions** reinforce important principles.
- **Essays by six leading astronomers**—two *new* to this edition—let the reader share in the excitement of scientific discovery.
- Recent discoveries are interwoven throughout, bringing our picture of the universe ***fully up to date.***
- In particular, this fourth edition has allowed ***expanded*** **coverage of the stars and galaxies,** while trimming some of the details of planetary astronomy.
- I have also *revised* overly intricate discussions so that **complex topics are more easily covered** or omitted at the discretion of each instructor.

As we shall now see in more detail, each of these features reflects the text's consistent themes and pedagogical emphasis. Let me begin with those features that build most closely on the strengths of previous editions.

Chapters are organized to emphasize scientific discovery

The text's traditional Earth-outward organization stresses how our understanding of the universe has developed. By moving outward from the planets to the stars and galaxies, we begin with celestial objects first observed by ancient astronomers using visible light.

The first six chapters introduce the foundations of astronomy, including naked-eye observations of eclipses and planetary motions and such basic tools as Kepler's laws, the properties of light, and the design of telescopes. Discussion of the formation of the solar system in Chapter 7 prepares the reader for the next ten chapters, which cover the solar system in outward order from the Sun.

Chapter 18 introduces stellar astronomy with the star that is most familiar to us: the Sun. The properties of stars are further described in Chapter 19, after which stellar evolution is described chronologically—from birth to death. Molecular clouds, star clusters, nebulae, neutron stars, and black holes are then presented in a sequence that mirrors the natural life of a star. These chapters thus

provide a unified description of the wide variety of objects that astronomers find scattered about the heavens.

A survey of the Milky Way in Chapter 25 is followed by two chapters on galaxies and quasars. The final chapters, on cosmology, further develop our understanding of the universe and its history. All of the "standard" cosmological issues are discussed in Chapter 28, and it would be quite appropriate to end an astronomy course with that chapter. Chapter 29 was created for those who wish to explore topics in which research is today proceeding at a fevered pitch. The student will learn that physicists are at the brink of tackling questions like: Why is there only one dimension of time yet three dimensions of space?

However, *Universe* does not rely solely on its Earth-outward sequence to show how our knowledge of the universe has grown. It is designed throughout to begin with historic questions and exciting observations. These observations, in turn, raise new questions that draw the reader on to the outer limits of our universe and our understanding.

Related chapters are grouped together for greater flexibility

Because this book is designed for both one- and two-term courses, it is more comprehensive than its sister text, *Discovering the Universe*. To make that comprehensive coverage accessible to a wide range of students, *Universe* has a flexible, modular structure that permits instructors to teach the topics in the order desired.

The book's 29 chapters are divided into two nearly equal parts, the first half dealing with introductory material and planetary astronomy, and the second half treating stars, galaxies, and cosmology. Instructors may emphasize either half of the book according to preference, covering more or less of the detail as time and the preparation of the students permit. For instance, a course on stellar astronomy could begin with the introductory chapters on gravitation and light (Chapters 4 and 5) and proceed directly to Chapter 18, which introduces the Sun and stars, without any loss of continuity.

Optional boxes with worked examples permit varied depth of coverage

Universe necessarily contains a little more mathematics than *Discovering the Universe*, but boxed inserts set aside much of the technical material. These boxes help instructors tailor their course to an appropriate depth of coverage and level of difficulty, and they permit students to locate and review topics more easily. All boxes may simply be omitted without loss of continuity.

Many boxes review the formulas that led to important discoveries. Others contain information, such as orbital and physical data for each planet, that will be useful for working the exercises. Still others take an idea raised in the text a step further.

For this edition, boxes that contain useful calculations always conclude with a highlighted worked example. The examples make the formulas easier to understand and better prepare readers for the end-of-chapter questions. The bright, new design of this edition also helps students to distinguish and to locate more easily those of the boxes that contain reference data useful in working questions.

Color illustrations are an essential part of this book

One glance at a color photograph of a planet's cloudtops or of the glowing gases of a nebula reveals significant details that cannot be gleaned from a black-and-white view. X-ray, infrared, and radio views of the sky can now be displayed comprehensibly in computer-generated false-color images. *Universe* was therefore the first to introduce full color to an astronomy text, and its selection of illustrations has been substantially updated to reflect how astronomy is practiced today.

Photographs new to this edition include a high-resolution map of Venus in Chapter 11, based on altimeter measurements. The next several chapters benefit from Hubble Space Telescope images, while Chapter 21 includes new images of 47 Tuscanae from the Anglo-Australian Telescope and of Betelgeuse from the U.S. National Optical Astronomy Observatories. Sally Heap's remarkable Hubble Space Telescope image of the central star of NGC 2440 has been added to Chapter 22, and Tony Tyson's stunning image of gravitational lensing in Abell 2218 elucidates discussion of dark matter in Chapter 25.

Artists' renderings within the text have been widely praised for their pedagogical effectiveness. This edition has corrected and simplified the labeling of many illustrations while adding new ones. For example, Chapter 18 now illustrates temperature changes and convection patterns within the Sun's layers. Particularly exciting are new supercomputer simulations of events that no Earth-based observer could ever have experienced. For example, Chapter 10 adds a colorful simulation of the formation of Mercury, and Chapter 22 vividly depicts instabilities that develop immediately after core bounce during the onset of a supernova explosion.

Chapters repeatedly summarize and review the main ideas

Part of helping students gain an appreciation for astronomy is guiding them through the most important ideas. Each chapter begins with a brief, one-paragraph abstract that gives the reader a clear idea of the chapter's contents.

The chapter headings, in the form of declarative sentences, then highlight main concepts. Read consecutively, these headings also make it easier to review the chapter.

Important terms are set in bold type where they are first defined, and they are defined again in the glossary at the back of the book, which also includes useful page references to the text. Each chapter concludes with both a list of these key terms and a summary of the essential facts in outline form.

End-of-chapter questions begin with a short summary of the relevant formulas; these "Tips and Tools" give students just enough of a hint to get them started. An annotated list of further readings rounds out each chapter's presentation.

End-of-chapter questions have been significantly enlarged

For this edition, the sets of questions have been rearranged and greatly enlarged. They are now grouped more simply into review, advanced, and discussion questions for ease of use. Answers to all questions that require computation appear at the end of the book, while the *Instructor's Manual* has step-by-step solutions that can be posted at the instructor's discretion.

In response to instructors' requests, greater care has been taken to include questions whose answers require reasoning rather than just memorization. Hence the range of questions is considerably expanded. To enhance student interest in astronomy, observational activities are also included as in previous editions, and attendant star charts are located at the back of the book.

Two additional essays introduce the personal views of leading astronomers

It is again a great pleasure to include the thoughts of renowned astronomers on topics of current interest. Six essays give this edition a depth and quality that could not have otherwise been possible:

"Why Astronomy?" (following Chapter 1), Sandra M. Faber, University of California, Santa Cruz, and Lick Observatory

"Astrology and Astronomy" (following Chapter 3), Owen Gingerich, Smithsonian Astrophysical Observatory and Harvard University

"Exploring the Planets" (following Chapter 12), Marcia Neugebauer, Jet Propulsion Laboratory

"The Solar Corona" (following Chapter 18), Arthur B. C. Walker, Jr., Stanford University

"The Great Attractor" (following Chapter 26), Alan Dressler, Carnegie Institution of Washington

"The Edge of Spacetime" (following Chapter 28), Stephen W. Hawking, University of Cambridge

I am particularly grateful to Dr. Gingerich, who has revised his essay so as to develop still further the historical background to modern science, and to Dr. Neugebauer and Dr. Walker, whose essays are *new* to this edition and greatly enhance its coverage.

This edition has an increased emphasis on stellar and galactic astronomy

The good judgment and extensive classroom experience of numerous text users, reviewers, and colleagues have inspired me to expand the treatment of stellar and galactic astronomy at the expense of planetary astronomy in this edition. Some consolidation in the planetary chapters involved thorough reorganization with the student in mind. For instance, Chapter 7 has been streamlined and reorganized, with the addition of two new sections, to make this overview of the solar system easier to follow, while the Moon's history, previously scattered throughout Chapter 9, has now been collected in one location. Among many other examples, in Chapter 16 the discussion of the interiors of Uranus and Neptune has been combined, providing a better lead-in to coverage of their magnetic fields.

Beginning with the Sun in Chapter 18, I have added significant material. For example, more details of the proton–proton chain have been spelled out in a box accompanying Chapter 18, and Chapter 19, on the nature of stars, has a much improved discussion of the distance modulus and the luminosity function near the Sun. Chapter 21 has been beefed up to include overcontact systems and long-period (Mira-type) variables. Chapter 22 now describes dredge-up in red giants and AGB stars; also included are a brief discussion of carbon stars and a characterization of Type Ia, Type Ib, and Type II supernovae.

Chapter 25 on the Milky Way now includes high-velocity stars, along with a box on the Local Bubble and the Geminga Pulsar. New topics in Chapter 27 include a discussion of nonthermal emission, superluminal motion, and the Eddington limit.

Coverage has been brought thoroughly up to date

The extensive revision of the sections on both planetary and stellar astronomy has given me the chance to update this edition to within only weeks of publication—right through the summer of 1993. Some of the additions are reflected in the dramatic new color images already mentioned. Among many other important changes, Chapter 8 on the Earth now includes discussion of repeated cycles of

supercontinent formation and breakup. The latest ideas about Mercury's iron core have been added to Chapter 10, and Chapter 11 is much enhanced by the recent discoveries about Venus from *Magellan*.

The latest word about such planned and ongoing missions as *Cassini* and the ill-fated *Mars Observer* has been included, and in Chapter 18 the discussion of solar neutrinos has been updated to include latest results from GALLEX and SAGE. The discussion of Sagittarius A* in Chapter 25 has also been updated; the entire section on galaxy evolution has been rewritten and is now based primarily on Hubble Space Telescope observations by Alan Dressler and others. Finally, the Afterword on the search for extraterrestrial intelligence now includes a discussion of NASA's Microwave Observing Project, as well as ongoing projects at Ohio State, Berkeley, and Harvard and other recent proposals.

This edition also makes many complex topics more manageable

An important result of this revision has been to make difficult discussions more accessible to students. I also took this opportunity to restructure several chapters so that they begin with basic observations; speculative topics are left to the end of the chapter, where they may be more easily omitted. I have in fact rechecked every section for clarity at the sentence level, eliminated several more challenging boxes, and moved some complex text discussions to new boxes, where they can be better supported by worked examples or simply omitted.

The more flexible coverage will be evident, for example, in Chapter 5, which now leaves many details of spectral lines and energy-level diagrams to a box, so as to make the discussion of the Bohr model clearer. Other boxes in that chapter include added worked examples of Wien's law, the Stefan–Boltzmann law, and Doppler shifts. A new box takes up details of the solar spectra in Chapter 19, a box in Chapter 25 applies Kepler's laws to the Sun's orbit in our Galaxy, while a box in Chapter 27 compares the redshift and cosmological parameters.

Some of the cuts, particularly in planetary astronomy, have already been mentioned, but encyclopedic aspects of the previous edition have generally been curtailed. For example, a box listing *all* the successful missions to the Moon has been deleted, although a short section on manned lunar exploration remains.

Chapter 18 has been turned inside-out, to begin with basic observation of the Sun's atmosphere rather than with the physics of the solar interior. Also at the request of many instructors, I have clarified the model of spiral-arm formation in Chapter 25.

I have completely rewritten Chapter 27 on quasars and active galaxies to follow a historical approach, from the discovery of high redshifts to the "unified model," to show more clearly how science is done. Finally, Chapter 29 now places highly speculative issues (GUTs, TOEs, and Kaluza–Klein theories) only in the second half of the chapter, and Feynman diagrams no longer appear.

Supplementary materials include a greater variety of still and moving images

The new **Instructor's Manual and Resource Guide,** prepared by George A. Carlson of Citrus College, contains chapter synopses and outlines, hints for teaching and discussion, a current list of resources for teaching that includes audiovisual materials as well as readings, and fully worked out solutions to the computational problems in the book.

Both **Overhead Transparencies** and **Slides** containing a selection of 100 color drawings from the text are also available. A **Computerized Test Bank,** available in Macintosh and IBM formats, has been revised and updated by T. Alan Clark and William J. F. Wilson of the University of Calgary to include some 2000 multiple-choice questions, indexed by chapter and topic. Newly included are chapter outlines, which are convenient for class distribution or as a basis for lectures. A printed test bank is also available.

New for this edition are **Active Sun Videos** produced by Lockheed Research Laboratory. These self-contained videos highlight recent advances in high-resolution solar astronomy that are difficult to convey in a textbook. The series features recent discoveries about the photosphere, sunspots, and the corona.

In addition, two 45-minute ***chapter-specific* Video Lectures** are available. These tapes of my lectures were made during a meeting of the Astronomical Society of the Pacific at the University of Wisconsin. *Black Holes and Warped Spacetime* covers most of Chapter 24. *Cosmology and the Creation of the Universe* is designed to be an entertaining introduction to Chapter 28.

Also available for the first time is *Gems of Hubble*, an **Electronic PictureBook** of images recently obtained by the Hubble Space Telescope. These exceptional images, each with a detailed caption, are part of a HyperCard stack and so may be quickly selected and presented using a Macintosh computer.

For more information, please contact your W. H. Freeman representative.

Acknowledgments

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Although we have made a valiant effort to make this an error-free edition, some mistakes may have crept in. I would appreciate hearing from anyone who finds an error or who wishes to comment on the text. You may write to me in care of the publisher. I will personally respond to all correspondence.

William J. Kaufmann III
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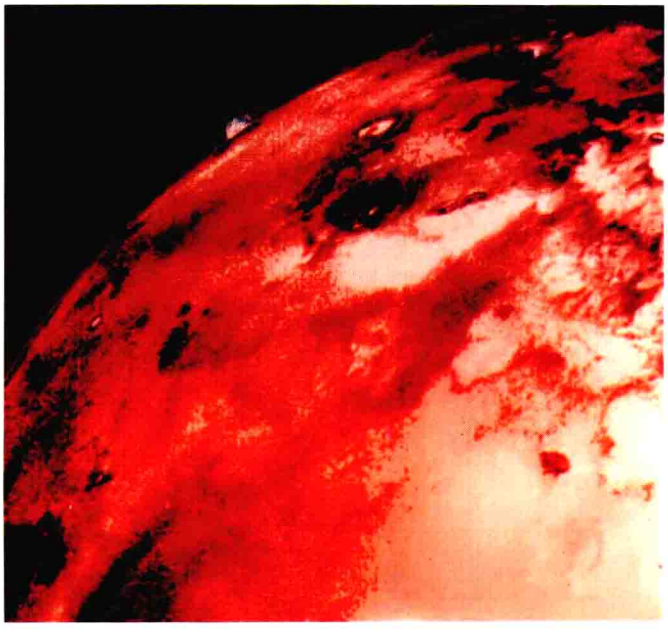

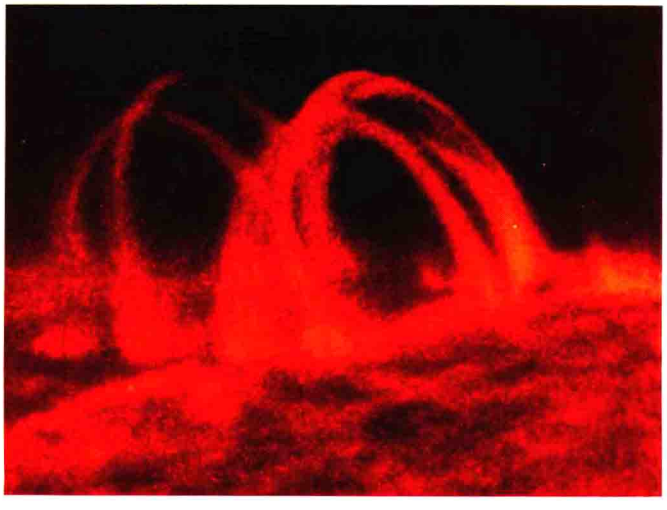

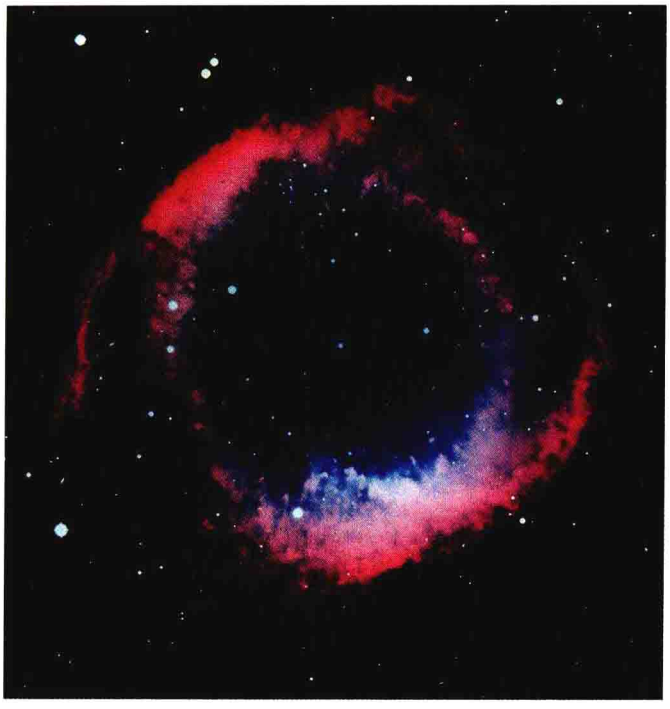

GALAXIES AND COSMOLOGY