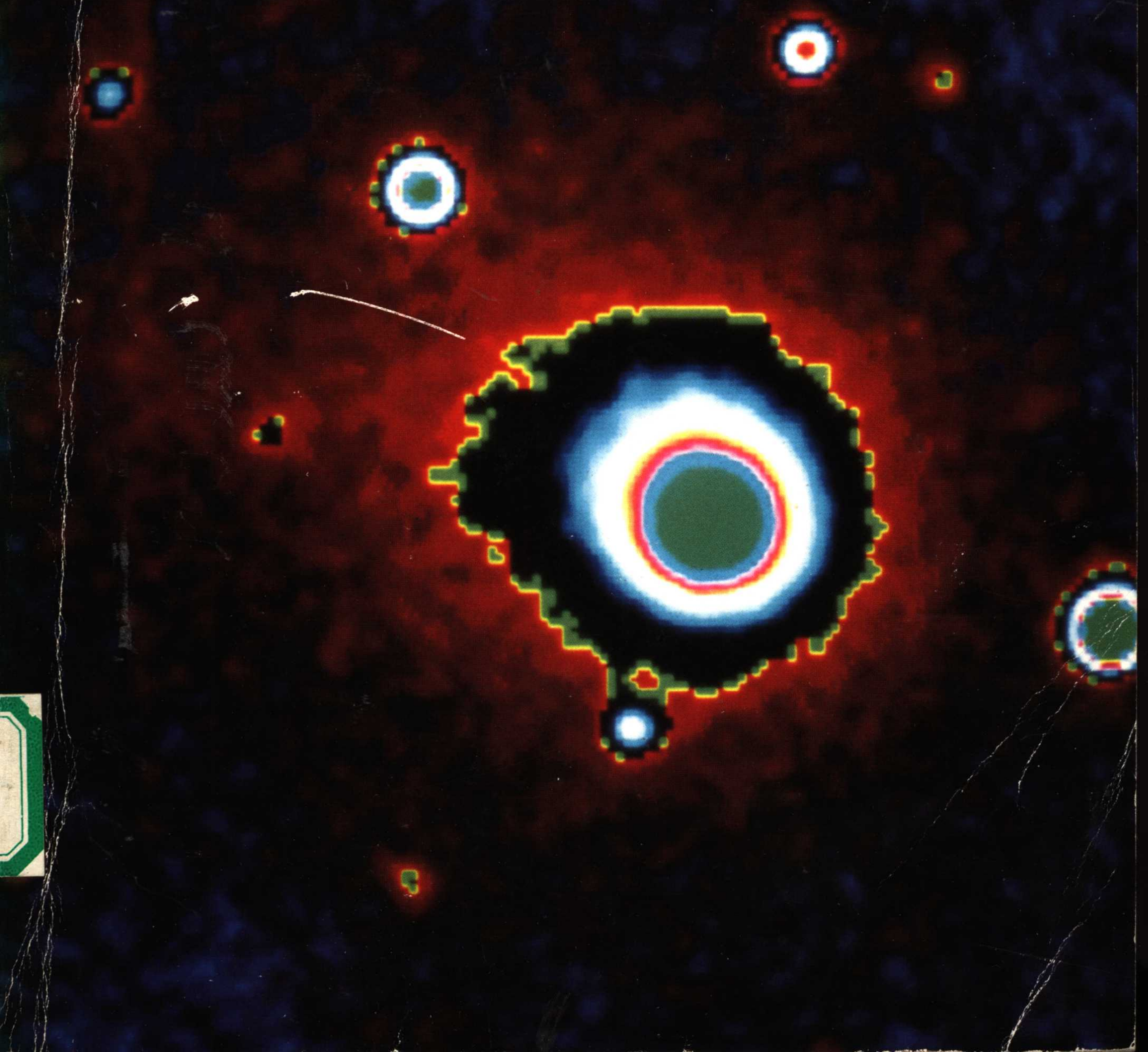
horizons

Exploring the Universe

1987 EDITION

Michael A. Seeds



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Exploring the Universe

1987 EDITION

Michael A. Seeds

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Franklin and Marshall College

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For Janet and Katie

A software package and an instructor's manual are available to accompany Horizons: Exploring the Universe, 1987 Edition.

The pages containing the star charts (following the index) are perforated so that students and instructors can separate them from the text for ease of use.

Cover Photograph: Computer enhancement of an image of Halley's Comet taken September 23, 1985, with the 3-m telescope at Lick Observatory. The color contours reveal differences in the intensity of light. (© 1985 Hyron Spinrad, Patrick McCarthy, and Michael Strauss)

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Preface

The body of astronomical knowledge resembles a marionette with its strings tangled. Each fact or observation is connected by inferences, assumptions, and theories to other facts and observations and to general principles. The teacher's task is to untangle this marionette and make clear to students the logic of the connections. Just as the marionette has inherent in its design an untangled state that makes the connections function properly, the body of astronomical knowledge has in its structure an untangled state that makes the logic of the inferences, assumptions, and theories clearest. In this book, I have attempted to present astronomy in that state of minimum tangle.

The order of topics in an astronomy course is not merely a matter of taste. By considering stars, galaxies, cosmology, and the solar system in that order, we simplify many of the evidential arguments and intuitive concepts so important to understanding astronomy. For example, by discussing star formation before the solar system, students recognize the solar nebula for what it was, a natural by-product of star formation. More important, by studying stars, galaxies, and cosmology first, students return to the solar system with a cosmic perspective on nature that places them and their planet into the universe rather than constructing a universe around them.

In addition to describing astronomy, this book tries to describe the nature of scientific study. We want our students to distinguish clearly between observation and theory, between evidence and conclusion. We want them to understand how models are constructed, tested, and improved or discarded. Consequently, I have tried to distinguish clearly between observational evidence and theoretical synthesis.

More important than the mechanisms of science is the personality of science. We want our students to understand how the community of science evaluates a new hypothesis. We must show how controversy among scientists is not a sign of weakness but a desirable means to better understanding. Most of all, we want our students to see science as a human activity that is challenging and rewarding.

Perhaps the most important goal in teaching any introductory astronomy course is to place our students in nature, to illustrate our role in the universe. If that is our goal, then we cannot think of astronomy as an accumulation of facts. Facts are merely data and can be meaningful only when they are synthesized into a consistent description of nature. Thus, this book views astronomy as a small number of basic physical processes that are responsible for a wide variety of phenomena and that explain a diverse assortment of objects. For example, galaxies, star clusters, individual stars, and planets are all expressions of the same process—gravitational contraction. Only the scale is different. Emphasizing processes presents astronomy not as a collection of unrelated facts but as a unified body of knowledge.

The most important astronomical process is evolution—the gradual, natural, irresistible transformation of a celestial body as it passes through stages in its formation, development, and ultimate dissolution. Stellar evolution is the principal example of astronomical change, and students must understand stellar evolution to understand the evolution of other celestial bodies. Of course, the ultimate evolutionary question is the origin of things, including the origin of the universe, galaxies, stars, planets, and life. The study of astronomical origins is an important part of this book.

Because most students cannot leap into a discussion of the origin of stars on page one, the first three chapters provide a transition from an earthbound frame of reference to an astronomical view of nature. Chapter 3 on the history of astronomy not only provides important background to place astronomy in historical context, but it also covers much of the basic physics needed to understand what follows.

Chapters 5 and 6 are closely related. Chapter 5 discusses the origin of spectra and the way astronomers analyze spectra. Chapter 6 applies these techniques to a study of the sun. In addition, Chapter 6 clearly establishes the sun as a star and leads the students to think of stars in general. Whatever the chapter topics, from Chapter 1 through Chapter 6, they gradually lead the students away from a self-centered conception of the sky overhead and closer to a disembodied view of stars as objects.

Because this book is intended for nonscience majors, it does not rely on mathematical reasoning. However, because science is fundamentally a quantitative discipline and because students should see that aspect of science, some mathematical discussions are included in boxes. None of these mathematical boxes is necessary to the development of the astronomical principles, and they can be deleted. For those who wish to include mathematics, examples have been worked in the boxes, and problems requiring mathematical skills have been placed at the end of each chapter.

Instructors familiar with the first edition of this book will notice that the second edition uses the SI metric units with only a few exceptions. This change seems called for to make the units agree with those students may have learned in high school science courses. The biggest change is from angstroms to nanometers. To all those instructors who, like the author, learned to think in angstroms, I apologize.

The only consistent exception to SI units is density, which is expressed in grams per cubic centimeter. Because the human hand can enclose a cubic centimeter but cannot enclose a cubic meter, the cgs units give a better "feel" for density than the SI units.

Each chapter ends with a group of aids to students and instructor. Several chapters end with a "Perspective" set off from the rest of the text. Perspectives introduce new and interesting ideas that allow students to review and apply the principles covered in the chapter. Some Perspectives discuss the development of a theory, the synthesis of hypotheses from data, the testing of theories by observation, and the meaning of statistical evidence.

Additional end-of-chapter materials include a chapter summary, a list of new terms, questions, problems, and recommended readings. The first time the new terms appear in the text they are **boldface**. These same terms appear in the glossary with page references. The recommended reading, which is intended for the student, ranges from *National Geographic* to *Science*. Instructors may wish to guide students in selecting appropriate reading material. The review questions are nonquantitative and could lead to essay answers. The discussion questions are more general and often go beyond the contents of the chapter. The problems are quantitative or involve mathematical reasoning. Answers to even-numbered problems appear at the end of the book, and answers to odd-numbered problems are given in the *Instructor's Resource Manual.*

This book contains a number of items that will encourage students to look at the sky. Chapters 2, 7, 10, and 15 conclude with short Observational Activities. These will guide students in making simple observations and in thinking about the implications of what they see. Chapter 15 contains a special section to help students locate Halley's Comet in 1986.

Appendices, a glossary, answers to the even-numbered problems, an index, and star charts follow the tables. Appendix A is a discussion of astrology, UFOs, and pseudoscience in general. Appendix B contains a discussion of astronomical coordinates and time. The remaining appendices contain notes on exponential notation, temperature scales, constants, and astronomical data.

The color plates in this book were selected to use color to illustrate such important points as the formation of spectra, the contours of radio galaxies, and the color of Mars. The rapid rise of computer manipulation of images makes such color important in a number of discussions through the text.

The reviewers who helped in the development of this book were Thomas Bullock, West Valley College; John J. Cowan, University of Oklahoma; Paul Feldker, St. Louis Community College; Martin L. Goodson, Delta College; Thomas L. Johnson, Ferris State College; J. Gordon Likely, University of Minnesota; Melvyn Oremland, Pace University; B. E. Powell, West Georgia College; C. W. Price, Millersville State University; Lawrence Ramsey, Pennsylvania State University; John B. Schaefer, Geneva College; Michael Stewart, San Antonio College; David Theison, University of Maryland; Theodore D. Violett, Western State College of Colorado; Daniel W. Weedman, Pennsylvania State University; Kenneth Yoss, University of Illinois.

I would like to thank those people listed in the figure captions for kindly providing photographs and diagrams.

My appreciation also goes to the staffs of the following institutions for their assistance in providing figures: The Anglo-Australian Observatory, AstroMedia Corporation, *The Astrophysical Journal*, Ames Research Center, Bell Laboratories, Brookhaven National Laboratories, Celestron International, U.S. Geological Survey, High Altitude Observatory, Jet Propulsion Laboratories, Johnson Space Center, Kitt Peak National Observatory, Lowell Observatory, Lunar and Planetary Laboratory, Martin Marietta AeroSpace Corporation, Mount Wilson and Las Campanas Observatories, National Aeronautics and Space Administration, National Radio Astronomy Observatory, Palomar Observatory, Royal Observatory, Edinburgh, and Yerkes Observatory. Many Voyager, Pioneer, and Mariner photographs were provided by the National Space Science Data Center.

Special thanks go to Tom Nerney and Jerilyn Emori of Wadsworth Publishing Company and Greg Hubit of Bookworks, without whom this second edition would not have been possible.

Finally, I would like to thank my wife Janet for allowing me to let the window sills go unpainted one more summer.

Michael A. Seeds
Lancaster, Pennsylvania

A Note from the Publisher

Since 1984, when the second edition of *Horizons: Exploring the Universe* was written, astronomers have increasingly come to accept black holes as the power sources at the center of active galactic nuclei, they are analyzing exciting new information about the structure of Uranus' rings, and they've photographed the nucleus of a comet. New telescopes, detectors, and computer processing techniques are allowing them to map the largest known structures of the universe in ever more revealing detail.

The rapid pace of such discoveries makes it difficult for people to keep up with the most recent advances. It's particularly challenging for textbooks to remain current because of the time needed to plan and publish them. This 1987 Edition of *Horizons* is our contribution toward providing instructors and students with the most accurate and up-to-date information available in this continually changing field. Incorporating the latest astronomical discoveries and research, Michael Seeds has solidly updated sections of the text, included many new photographs and illustrations, and improved the overall clarity. The text's basic premise—an emphasis on astrophysical processes and scientific reasoning using the contemporary "stars first" order—remains the same.

The 1987 Edition features discussions on recent changes in HH46, bipolar flow theory, and the solar neutrino problem (Chapter 8); and expanded, updated discussions on supernova explosions, pulsars, x-ray binaries, and black holes—including an imaginary leap into a black hole (Chapter 9). The author updates and clarifies material on the Milky Way, including recent information on the galactic corona and nucleus (Chapter 10); adds new, recent information on Cepheids, the Small Magellanic Cloud (Chapter 11), Seyfert galaxies, active galactic nuclei, and gravitational lenses (Chapter 12); and expands the discussion of inflationary universe scenarios (Chapter 13). There's new material on comets from the Comet Halley probes and the ICE flyby, plus a new section on comet geology (Chapter 15); expanded coverage of Uranus—its magnetic field, cloud belts, rings, and satellites—with new photos and diagrams (Chapter 17); plus the latest information on new telescope technology, including material on earth and space telescopes currently being designed (Chapter 4).

We view this revision primarily as a necessary update, rather than as a major change in the text itself (which could require substantial revision of an instructor's course notes). Therefore, we have been careful to keep the original section-by-section sequence, chapter length, and book length intact, and have integrated the new material smoothly into the book's original structure. We sincerely believe these changes will assist instructors in their efforts to teach a current, accurate, and effective course in astronomy. And we hope that students will continue to be fascinated and excited to explore the scientific wonders of the universe with the help of *Horizons*.

To the Reader

You will approach retirement around the year 2035, and your children about 2060. Your grandchildren will not be retiring until almost 2100. You and your family will live through a century of exploration unlike any in the history of this planet. You will see explorers return to the moon, and your children could be the first colonists in lunar cities. Your grandchildren may reach Mars, mine the asteroid belt, explore the icy satellites of Jupiter and Saturn, or leave the solar system bound for the stars. A century ago the airplane had not been invented. Whatever humanity is like a century in the future, we can guess that it will be deeply involved in the exploration of the solar system. Astronomy, the study of the universe beyond the clouds, helps us understand what we will find when we leave Earth.

Why Bother? Living in the next century might be enough justification for taking an astronomy course, but there are other reasons. The coming years will see tremendous advances in science and technology, advances that will confuse anyone not familiar with how science progresses from data to hypothesis to theory to natural law. Should your state permit nuclear waste disposal sites? Should you support construction of orbiting solar power stations? Should you give your children massive doses of vitamin C to combat colds? To resolve such technical issues, you need to apply some of the methods of science. Thus, as you study astronomy in the pages that follow, look at it as an example of scientific reasoning. Distinguish between data and theory, and notice how hypotheses are tested over and over.

Yet another reason for taking an astronomy course is to satisfy your natural curiosity. Having heard about black holes, the expanding universe, or the rings of Saturn, you may want to know more about them. Satisfying your own curiosity is the most noble reason for studying anything.

Curiosity might lead you to consider astronomy as a career, but you should know that the field is very small and jobs are hard to find. Instead, you might consider astronomy as a hobby—an activity for personal satisfaction and enrichment. The magazines listed here will keep you up to date with the rapid advances in the field and give you some ideas for further projects, such as telescope building and astronomical photography:

Astronomy, 411 East Mason St., P.O. Box 92788, Milwaukee, WI 53202
The Griffith Observer, 2800 East Observatory Road, Los Angeles, CA 90027
Mercury, Astronomical Society of the Pacific, 1290 24th Ave., San Francisco, CA 94122
Sky and Telescope, Sky Publishing Corporation, 49 Bay State Rd., Cambridge, MA 02238

Four Questions. Although there are many ways of organizing a study of astronomy, we will concentrate on the answers to four fundamental questions. First, *What does the sky look like and how do its motions arise?* When we look at the night sky, we can see the stars, the moon, and five of the planets in our solar system. Though the stars move very slowly, the moon and planets move relatively quickly across the sky as they follow their orbits. In addition, we live on a spherical planet that rotates on its axis once a day and orbits the sun once a year. These motions produce corresponding motions in the sky as we see it. Our view of the universe corresponds to the view of an amusement park seen from the spinning car of a carnival ride. As we try to answer our first question, we will gain an insight into the relationship of the earth to the rest of the universe.

Our second question is, *What are stars?* The universe is filled with stars and we must understand how they work if we are to understand how nature acts on the astronomical scale. Modern astronomers have deduced that stars are enormous, hot balls of gas. Our sun is a perfectly normal star. It is 109 times larger in diameter than Earth, and its surface temperature is about 6000 K. The temperature at its center is about 14,000,000 K.

Stars are held together by their own gravity, producing very high pressure and temperature near their centers. Under these extreme conditions, atoms fuse together in nuclear reactions, releasing tremendous amounts of energy. Since most stars are about 80 percent hydrogen, we can think of a star as a giant hydrogen bomb continuously exploding. The star is caught in a tug of war between its gravity, which tries to make it collapse into itself, and the nuclear reactions at its center, which try to blow it apart. When the fuel runs out, the nuclear reactions stop, gravity wins, and the star collapses. How stars die is a subject we will save for a later chapter.

We must study stars not only as individuals, but in larger groupings. All of the stars we see in the sky are part of our Milky Way galaxy, a great wheel of stars 100,000 ly in diameter. The sun is just one of the 100 billion stars in the galaxy, each moving in its own orbit around the center. In addition, our galaxy is merely one of millions of galaxies scattered through space. Some, like our own, are disk-shaped and show beautiful spiral patterns of bright stars. Others are plain, featureless clouds of stars.

We understand only part of the story of galaxies. Their evolution is connected to the way stars live and die, but many of the details are still unknown.

The third question we will consider is, *How did the universe itself begin?* Modern astronomers have found some exciting clues to the origin of the universe, but the clues don't quite fit together. At the moment we have a theory called the big bang. According to this theory, the universe began 10 to 20 billion years ago as an extremely hot, dense gas. As that gas expanded and cooled, it broke into clouds and then formed galaxies of stars.

We will find a number of important clues to the origin of the universe. For example, when we look at galaxies we will find they appear to be moving away from each other, suggesting that the universe is still expanding.

Finally, our fourth question: *What is the origin of the solar system?* The nine planets that circle the sun should be easier to study than distant galaxies, but planets are very complex objects. We can't be sure of the details, but we can infer that the planets formed with the sun about 5 billion years ago. Since that time, the planets have evolved in complicated ways to reach their present state. If we can unravel the processes that affected the ancient earth, we may uncover clues to the origin of life and the future of our planet. That may even help us consider the possibility that life exists on other planets orbiting other stars.

Just for You. Your astronomy course is different from most other college courses, which concern knowledge and skills you will use professionally. If you become a lawyer, your government courses will be valuable, and if you go into business, your mathematics and accounting courses will pay dividends. In a sense, you are taking these courses now and will later trade the knowledge you gain to an employer in return for a good job. Astronomy is different because it is just for you. It will show you our tiny planet spinning in space amid a vast cosmos of stars and galaxies. It will take you from the first moment of creation to the end of the universe. You will see our planet form, life develop, and our sun die. This knowledge has no monetary value, but it is priceless if you are to appreciate your existence as a human being.

Astronomy will change you. It will not just expand your horizons, it will do away with them. You will see humanity as part of a complex and beautiful universe. If by the end of this course you do not think of yourself and society differently, if you don't feel excited, challenged, and a bit frightened, then you haven't been paying attention.

M. A. S.

Contents

The Earth and Sky

. . . that inverted Bowl we call the Sky.
The Rubaiyat of Omar Khayyam,
trans. Edward FitzGerald

If we could leave the Earth and travel out toward the stars at the speed of light, we would cross the orbit of the moon in about one second. We would pass the sun in eight minutes, but it would take us four years to reach the next nearest star. If we continued our journey for thousands of years, we would pass star after star as we traveled farther away from our planet. Some stars would shine nearly a million times brighter than our sun and some would glow thousands of times fainter.

With this chapter we begin such a journey of imagination that will take us deep into space to see stars forming and stars dying. We will discover massive black holes and tiny specks of dust. Our goal in this chapter is less dramatic, but it will tax our imaginations no less than the strangest black hole. We must learn to recognize the sky not as a great ceiling overhead but as the rest of the universe as seen from our planet.

The sky does look like a dome overhead or, more precisely, like a great sphere surrounding the Earth and rotating slowly, carrying the stars westward across the sky. Actually, of course, it is Earth that turns, making the sky seem to rotate around us, and the thousands of visible stars are really other suns scattered through space—some nearby and some far away.

The four-day-old crescent moon and Venus setting. Exposures were made every 8 minutes, illustrating how the eastward rotation of Earth causes celestial objects to move westward across the sky. Note also the motion of the moon relative to Venus. (Photo by William P. Sterne, Jr.)

The Stars

Constellations. For thousands of years cultures have named patterns of stars. The ancient Arabs named a pattern of stars Al Jabbār, the Giant. To the Egyptians those stars were the god Osiris, to the Hindus they were Mriga, the stag, and to the Greeks they were Oarion, the Hunter. We know them as Orion.

The sky is rich with named star patterns often called *asterisms,* but only 88 are recognized by international agreement among astronomers as **constellations** (Figure 1-1). The Big Dipper, for example, is a well-known asterism, but it is only a part of the constellation Ursa Major, The Great Bear.

Keep in mind that the stars that make up a constellation are not usually physically associated with each other. Some may be much farther from Earth than others. The only thing they share is that they lie in roughly the same direction from earth.

About half of today's 88 constellations were named in ancient times. The oldest seem to have originated in Mesopotamia over 5000 years ago: others were added by Babylonian, Egyptian, and Greek astronomers. Some constellations had religious significance, some honored mythical heroes, and some appear to have been navigational aids for sailors. The motions of the distant stars through space have changed these constellations very little if at all since they were first named, and they remain a rich heritage from long-dead civilizations.

To the ancients, a constellation was a loose grouping of stars. A star could even belong to more than one constellation, as in the case of Alpheratz in the constellation of Andromeda and Pegasus (Figure 1-2a). In 1925, the world's astronomers agreed to divide the sky into 88 regions roughly following the common constellations. Thus every star in the sky is assigned to one constellation. This solves the problem of Alpheratz, making it part of Andromeda (Figure 1-2b).

When the first explorers sailed into the southern oceans, they saw parts of the sky that ancient astronomers had never seen. Those explorers named the new star patterns they saw there after familiar objects. About the same time, astronomers noticed that the ancient constellations left unnamed certain regions of the northern sky that did not contain bright stars. Thus they suggested new constellations to fill these gaps. Some of these added constellations were later dropped, but others came into common usage.

The names of these 44 modern constellations are sometimes strangely modern, such as Telescopium (the Telescope) and Antlia (the Air Pump). Most of these constellations are in the south, but a few such as Lacerta (the Lizard) are faint groupings in the northern sky. Box 1-1 introduces the brighter constellations.

Modern astronomers still use the constellations as a convenient way of referring to areas of the sky. But merely naming the constellation in which a star is found does not identify it uniquely. Thus we must discuss ancient and modern ways of naming stars.

The Names of the Stars. The brightest stars were named thousands of years ago. Although the names of the constellations are in Latin, most star names come from ancient Arabic. Such names as Sirius (the Scorched One), Capella (the Little She-goat), and Aldebaran (the Follower of the Pleiades) are beautiful additions to the mythology of the sky.

Giving the stars individual names is not very helpful because we see thousands of stars, and

Figure 1-1
The constellations Orion and Taurus represent figures from Greek mythology. (Adapted from Duncan Bradford, Wonders of the Heavens, *Boston: John B. Russell, 1837)*

these names do not help us locate the star in the sky. Another way to identify stars is to assign Greek letters to the bright stars in a constellation in approximate order of brightness. Thus the brightest star is usually designated α (alpha), the second brightest β (beta), and so on. For almost all constellations, the letters follow the order of brightness (Figure 1-3). To identify a star in this way, we give the Greek letter followed by the genitive form of the constellation name, such as α Canis Majoris. This both identifies the star and constellation and gives us a clue to the brightness of the star. Compare this with the ancient name for this star, Sirius, which tells us nothing about location or brightness.

This method of identifying a star's brightness is only approximate. In order to discuss the sky with precision, we must have an ac-

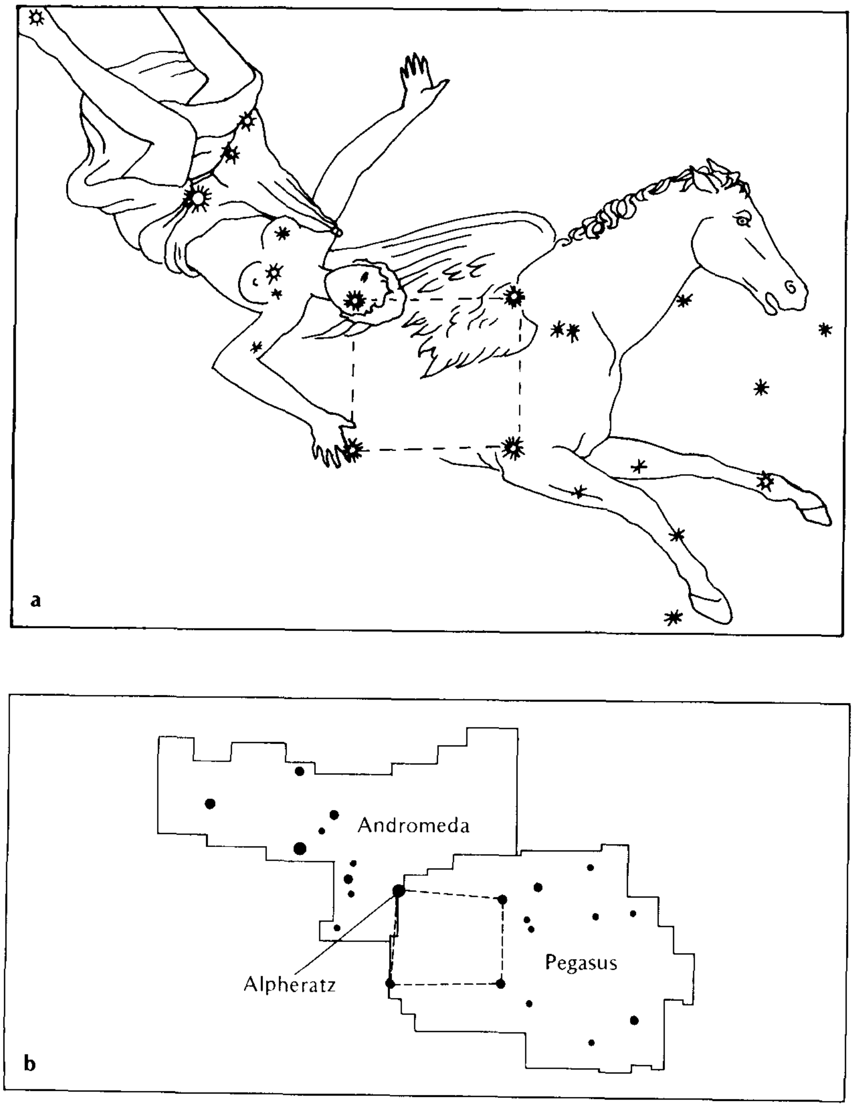

Figure 1-2
(a) The ancient constellations Andromeda and Pegasus share the star Alpheratz at the upper left corner of the great square of Pegasus. (Adapted from Duncan Bradford, Wonders of the Heavens, *Boston: John B. Russell, 1837) (b) Modern constellation boundaries assign Alpheratz to Andromeda.*