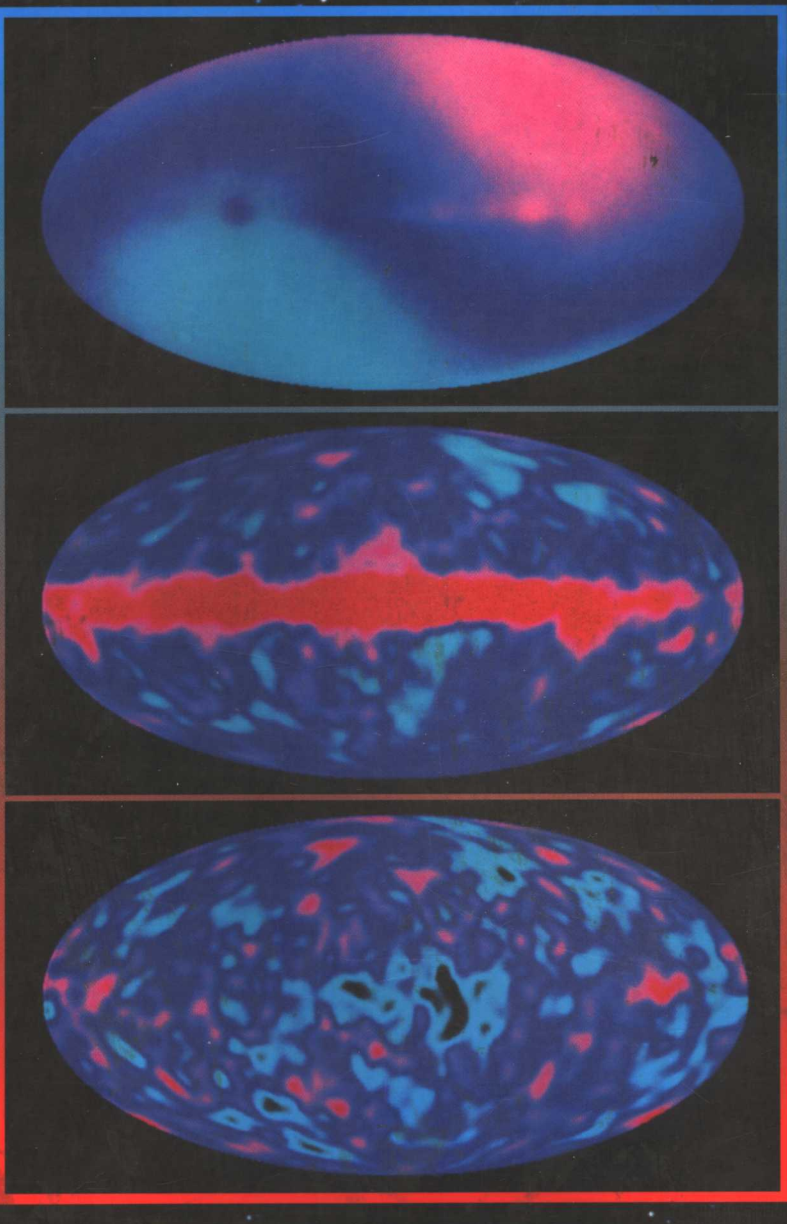
ASTRONOMY

From the Earth to the Universe

FOURTH EDITION



JAY M. PASACHOFF

1993 VERSION

Astronomy:

From the Earth to the Universe

Fourth Edition, 1993 Version

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Preface

Astronomy continues to flourish. The opening of the Keck 10-meter Telescope promises important discoveries. The Hubble Space Telescope, even with its flawed mirror, is now yielding science of high value. We hope that the repair mission scheduled for late 1993 and the second-generation instruments will allow the telescope to achieve its full potential. In the meantime, the Magellan spacecraft orbiting Venus and the Compton Gamma-Ray Observatory are giving spectacular results. Further, new electronic instruments and computer capabilities, new space missions to the outer planets, and advances in computational astronomy and in theory should continue to bring forth exciting results.

In *Astronomy: From the Earth to the Universe*, I try to describe the current state of astronomy, both the fundamentals of astronomical knowledge that have been built up over decades and the exciting advances that are now taking place. I try to cover all the branches of astronomy without slighting any of them; each teacher and each student may well find special interests that may be different from my own. One of my aims in writing this book is to educate voters and prospective voters in the hope that they will endorse candidates who will support scientific research in general and astronomical research in particular.

New to This Edition

It is particularly exciting for me to be able to use color images throughout (approximately 750 photographs and 250 drawings). Over the past few years, many new color images have become available and even vital for presenting astronomy. For one thing, many new images of astronomical objects have become available in color, both through careful application of film techniques for photographs taken with telescopes on Earth and through the use of electronic techniques with sensors on both ground-based telescopes and on spacecraft. Further, the computer reduction of data, now so fundamental and widespread, has led to the ability to present data with a third dimension—color—providing additional information to an image. Of course, I have also tried to use color intelligently in the diagrams, emphasizing or bringing out whenever possible aspects on which you should spend special attention.

I am especially proud that my texts are unique in that they have separate chapters covering branches of astronomy for which we newly have extensive information: Neptune is the most prominent example in this edition, as a result of the Voyager 2 flyby. Supernovae, with the new information from the brightest supernova in nearly 400 years, and comets, with the information from the recent apparition of Halley's Comet, are other examples of new chapters since the third edition. Other topics that receive here the separate chapters they deserve are pulsars/neutron stars, black holes, quasars, and the past and future of the universe, topics that are especially interesting to students and faculty alike.

Educational Approach

I have paid special attention to making the books readable by students and the information accessible to them. The stories of the development of individual fields of study, as for the individual planets, are somewhat chronological to give students an opportunity to see how knowledge has grown. The occasional mention of the names of the contemporary astronomers performing the research discussed personalizes astronomy and shows that it is a human science as well as giving credit where credit is due. Newton was not the last scientist worthy of being mentioned by name!

In writing this book, I share the goals of a commission on the college curriculum of the Association of American Colleges, which reported that "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."

I have tried to keep up with recent psychological research on the teaching of science and the understanding of concepts. My books, therefore, include many concrete examples that make scientific situations more understandable to many students. I continue to consult with my psychologist colleagues so as to be able to implement correctly some of the tenets of Piaget, while taking into account the results of post-Piagetan research.

Pedagogy

I have provided aids to make this book easy to read and to study from. Many diagrams provide interpretive information not on diagrams on the same topic in other texts: professors can compare among other texts, for example, the diagrams that explain the Doppler effect, or the ones for Hubble's law. Each section of the text is numbered to allow professors to include or omit parts of chapters. Some professors will choose to include discussions, for example, of the over four dozen new worlds photographed as moons of the giant planets in our solar system; others will choose to omit this material. Further, some sections and boxes appear with asterisks to show that these are especially easy to omit.

New vocabulary is italicized in the text, listed in the key words 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; some questions are straightforward and can be answered by merely reading the text, while others require more independent thought. Up-to-date appendixes provide some standard and much recent information on planets, star constellations, and non-stellar objects.

Ancillary Materials

Available free to all adopters of the 1993 Version are the following ancillaries:

Instructor's Resource Manual with Laboratory Experiments
This 400-page manual contains course outlines, answers to all questions in the text, lists of audiovisual aids and organizations, 11 laboratory experiments and exercises arranged for easy duplication, sample tests with an-

swers (8 quizzes and 9 exams), Test Bank objectives, and a 105-page set of notes linking each text chapter with its complementary *Project Universe* video series episode.

Saunders Astronomy Transparency Collection This comprehensive set contains 205 color overhead transparency acetates of conceptually-based artwork. Over half are enlarged reproductions of figures from the textbook. The others are supplemental illustrations that complement the text figures. A detailed guide arranged by topic accompanies the collection.

Saunders Astronomy Slide Collection The set of 205 transparency acetates is also available in 35-mm slide format.

Saunders Astronomy Video Tape This 93-minute VHS tape presents five NASA/JPL "movies," including a segment on images obtained from the Magellan Venus Orbiter. NOVA videotapes are also available.

Printed Test Bank This set of over 3200 questions in multiple choice and other formats was prepared by H. C. Snyder of St. Clair County Community College.

ExaMaster™ Computerized Test Bank for IBM and Macintosh The 3200 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.

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For Information about these ancillaries contact your local Saunders sales representative or call the Harcourt Brace Jovanovich College Department at (800) 237-2665.

Acknowledgments

The publishers and I have always placed a heavy premium on accuracy in my books, and we have made certain that the manuscript and proof have been read not only by students for clarity and style and by astronomy teachers for pedagogical reasons but also by research astronomers for scientific accuracy.

I would particularly like to thank the reviewers of all or large sections of the manuscript of this edition, who include Yervant Terzian (Cornell University), Alexander G. Smith (University of Florida), Joseph Veverka (Cornell University), Bruce Margon (University of Washington), Paul Hodge (University of Washington), Hyron Spinrad (University of California, Berkeley), Gary Mechler (Pima Community College), Leonard Muldawer (Temple University), Paul B. Campbell (Western Kentucky University), Gordon E. Baird (University of Mississippi), Robert L. Mutel (University of Iowa), and Gordon B. Thompson (Rutgers University).

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I appreciate the expert assistance in Williamstown of Susan Kaufman.

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Various members of my family have provided vital and valuable editorial services, in addition to their general support. My wife, Naomi Pasachoff, has taken time from her own projects to give expert readings of the various stages of proof. The participation of our daughters, Eloise and Deborah, in some of the proofreading is a source of great satisfaction to me. Their continued growth continues to be monitored alongside the Ahneghito meteorite. My father, Dr. Samuel S. Pasachoff, contributed so much to my books over the years. I also appreciate the counsel of my mother, Anne T. Pasachoff.

A Final Comment

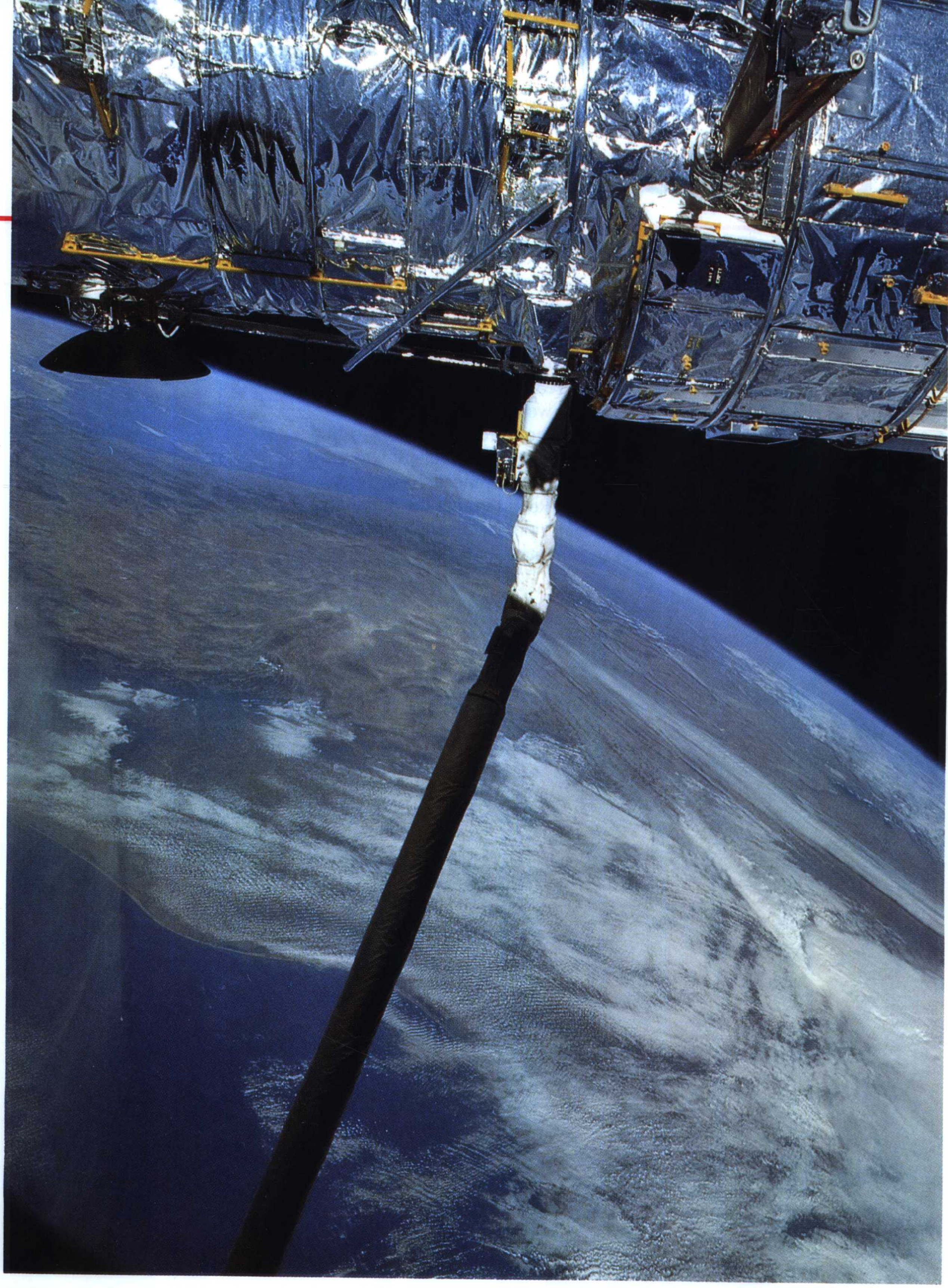
I am extremely grateful to all the individuals named for their assistance. Of course, it is I who have put this all together, and I alone am responsible for it. I appreciate hearing from readers. I invite you to write me at Williams College—Hopkins Observatory, Williamstown, MA 01267. I promise a personal response to each writer.

Jay M. Pasachoff
Williamstown, MA
June, 1992

This supernova remnant is spread over a wide area in the constellation Vela.

To the Student

Astronomy is a very varied subject, and you are sure to find some parts that interest you more than others. To get the most out of this text, you must read each chapter more than once. After you read the chapter the first time, you should go carefully through the list of key words, trying to identify or define each one. If you cannot do so, look up the word in the glossary and also find the definition that appears with the word the first time it was used in the chapter. The index will help you find these references. Next, read through the chapter again especially carefully. Read through the Summary, checking that you understand each of the major points. Finally, answer a selection of the questions at the end of the chapter.



Discovery's remote manipulator system hoists the Hubble Space Telescope (HST) over the Earth's horizon prior to deployment of HST's solar panels and antennae.

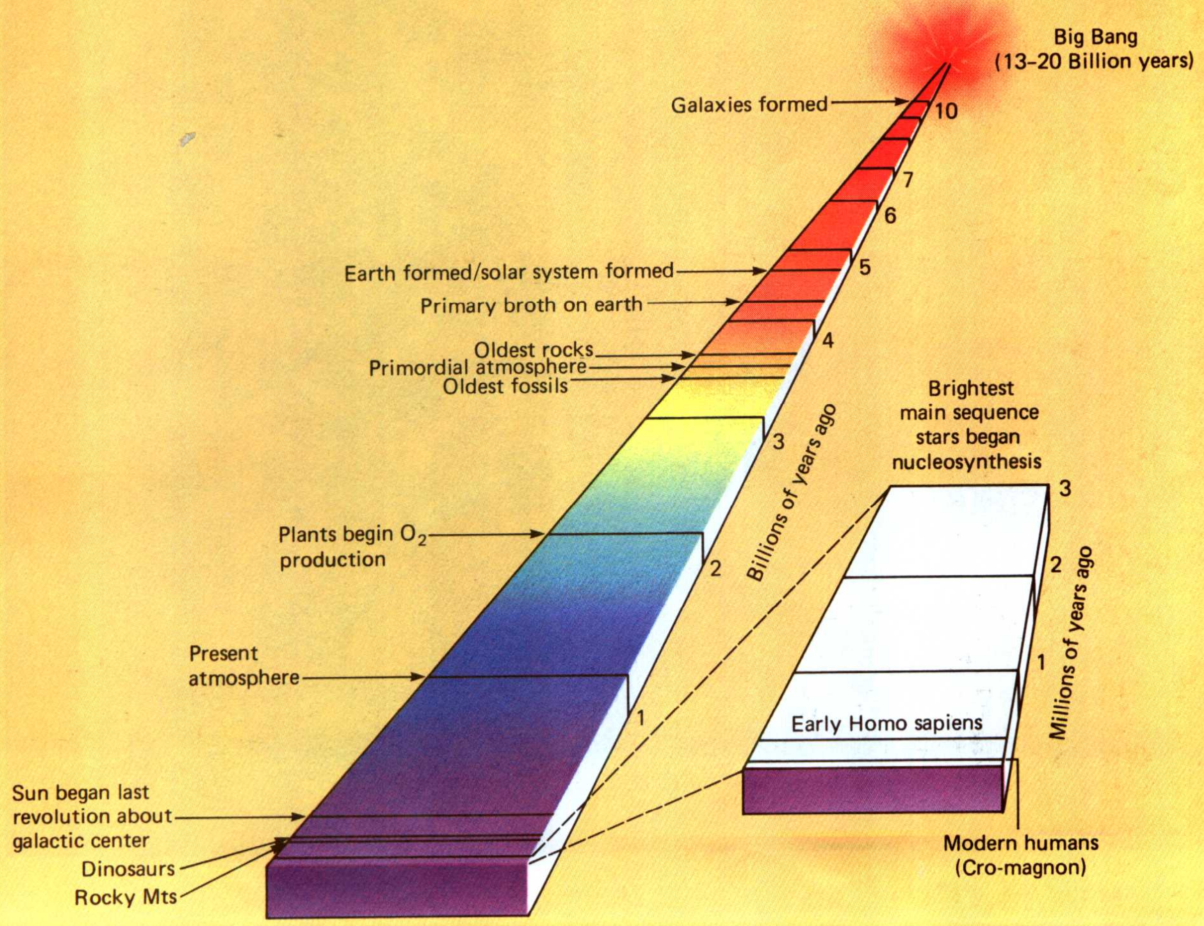
1

A Sense of the Universe

Let us consider that the time between the origin of the universe and the year 2000 is one day. Then it wasn't until nearly 5 p.m. that the Earth formed; the first fossils date from 7 p.m. The first humans appeared only 10 seconds ago, and it is only $1/400$ second since Columbus discovered America. The year 2000 will arrive in only $1/30{,}000$ second.

Still, the Sun should shine for another 7 hours; an astronomical time scale is much greater than the time scale of our daily lives. Astronomers use a wide range of technology and theories to find out about the universe, what is in it, and what its future will be. This book surveys what we have found and how we look.

A sense of time.



The reflection nebula NGC 6188.

The Universe: An Overview

1

Aims: To get a feeling for the variety of objects in the universe and a sense of scale

The universe is a place of great variety—after all, it has everything in it! Some of the things astronomers study are of a size and scale that we humans can easily comprehend: the planets, for instance. Most astronomical objects, however, are so large and so far away that our minds have trouble grasping their sizes and distances.

Moreover, astronomers study the very small in addition to the very large. Most everything we know comes from the study of energy travelling through space in the form of "radiation"—of which light and radio waves are examples. The radiation we receive from distant bodies is emitted by atoms, which are much too small to see with the unaided eye. Also, the properties of the large astronomical objects are often determined by changes that take place on a minuscule scale—that of atoms or their nuclear cores. Further, the evolution of the universe in its earliest stages depended on the still more fundamental particles within the nuclei. Thus the astronomer must be an expert in the study of the tiniest as well as the largest objects.

Such a variety of objects at very different distances from us or with very different properties often must be studied with widely differing techniques. Clearly, we use different methods to analyze the properties of solid particles like martian soil (using equipment in a spacecraft sitting on the martian surface) or the results of flying through Halley's Comet than we use to study the light, radio waves, or x-rays given off by a gaseous body like a quasar deep in space.

One method—*spectroscopy*—does link much of astronomy. Spectroscopy is a procedure that analyzes components of the light or other radiation that we receive from distant objects and studies these components in detail. Throughout this book, we shall return to spectroscopic methods time and again to study not only visible light but also other types of radiation. Of course, astronomers also make images—pictures—of some objects, such as planets, the Sun, and galaxies. We may also study the variation of the amount of light coming from a star or a galaxy over time, or send spacecraft to the Moon, planets, and comets.

The explosion of astronomical research in the last few decades has been fueled by our new ability to study radiation other than light—gamma rays, x-rays, ultraviolet radiation, infrared radiation, and radio waves. Astronomers' use of their new abilities to study such radiation is a major theme of this book. All the kinds of radiation together make up the *electromagnetic spectrum,* which we will discuss in Chapter 4. As we shall see there, we can think of radiation as waves, and all the types of radiation have similar properties except for the length of the waves. Still, although x-rays and visible light may be similar, our normal experiences tell us that very different techniques are necessary to study them.

The Earth's atmosphere shields us from most kinds of radiation, though light waves and radio waves do penetrate the atmosphere. Over the last 50 years, radio astronomy has become a major foundation of our astronomical knowledge. For the last 30 years, we have been able to send satellites into orbit outside the Earth's atmosphere, and we are no longer limited to the study of radio and visible (light) radiation. Many of the fascinating discoveries of recent years—the probable observations of giant black holes within our galaxy and other galaxies and quasars, for example—were made because of our newly extended senses. We will discuss how astronomers use all parts of the spectrum to help us understand the universe.

We will see, also, how we get information from direct sampling of bodies in our solar system and from cosmic rays (particles whizzing through space). These cosmic rays are atomic nuclei and subatomic particles moving through space, which are also known as "radiation," though they are different from the electromagnetic radiation we mentioned previously. We have also detected subatomic particles called neutrinos both from the Sun and, spectacularly, from the explosion of a distant star.

Further, we can now even observe the consequences of gravitational waves, whose existence is predicted by Einstein's general theory of relativity and confirmed from observations of a special pulsar. We shall discuss all these methods of astronomical research in the book; remember that the index provides page references.

1.1 A Sense of Scale

Let us try to get a sense of scale of the universe, starting with sizes that are part of our experience and then expanding toward the infinitely large. We can keep track of the size of our field of view as we expand in powers of 100: each diagram will show a square 100 times greater on a side.

In this book, we shall mostly use the International System of Units (Système International d'Unités, or SI for short), which is commonly used in almost all countries around the world and by scientists in the United States. The basic unit of length is the meter (symbol: m), which is equivalent to 39.37 inches, slightly more than a yard. The basic unit of mass is the kilogram (symbol: kg), and the basic unit of time is the second (symbol: s; we use "sec" in this book for added clarity). Prefixes (Appendix 1) are used to define larger or smaller units of these base quantities. The most frequently used prefixes are "milli-" (symbol: m), meaning 1/1000, and "kilo-" (symbol: k), meaning 1000 times. Thus 1 millimeter (1 mm) is 1/1000 of a meter, or about 0.04 inch, and a kilometer (1 km) is 1000 meters, or about 5/8 mile. For mass, the prefixes are used with "gram" (symbol: g), 1/1000 of the base unit "kilogram." We will keep track of the powers of 10 by which we multiply 1 m by writing as an exponent the number of tens we multiply together; 1000 m, for example, is 10^3 m, which is 1 km.

The meter is now defined in terms of how far light travels in a certain time. The speed of light in a vacuum (a space in which matter is absent) is, according to the "special theory of relativity" that Albert Einstein advanced in 1905 (Section 23.11), the greatest speed that is physically attainable. Light travels at about 300,000 km/sec (186,000 miles/sec), fast enough to circle the Earth 7 times in a single second. Even at that fantastic speed, we shall see that it would take years for us to reach the stars. Similarly, it has taken years for the light we see from stars to reach us, so we are really seeing the stars as they were years ago. In a sense, we are looking backward in time. The distance that light travels in a year is called a *light year* (ly); note that the light year is a unit of length rather than a unit of time even though the term "year" appears in it.

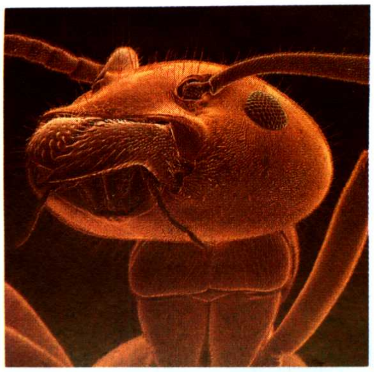


Figure 1–1 1 mm = 0.1 cm

Let us begin our journey through space with a view of something 1 mm across (Fig. 1–1), an electron microscope view of an ant. Every step we take will show a region 100 times larger in diameter than the previous picture.

A square 100 times larger on each side is 10 centimeters × 10 centimeters. (Since the area of a square is the length of a side squared, the area of a 10-cm square is 10,000 times the area of a 1-mm square.) The area encloses a flower (Fig. 1–2).

Figure 1–2 10 cm = 100 mm

Figure 1–3 10 m = 1000 cm

Here we move far enough away to see an area 10 meters on a side (Fig. 1–3).

A square 100 times larger on each side is now 1 kilometer square, about 250 acres. An aerial view of Boston shows how big an area this is (Fig. 1–4).

Figure 1–4 1 km = 10^3 m

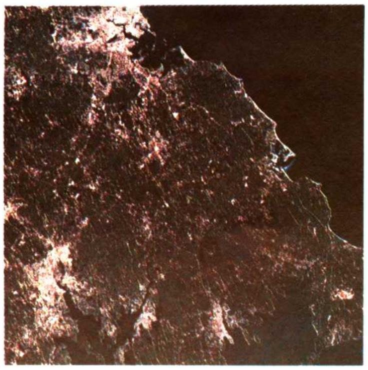


Figure 1–5 100 km = 10^5 m

The next square, 100 km on a side, encloses the cities of Boston and Providence. Note that though we are still bound to the limited area of the Earth, the area we can see is increasing rapidly (Fig. 1–5).

A square 10,000 km on a side covers nearly the entire Earth (Fig. 1–6).

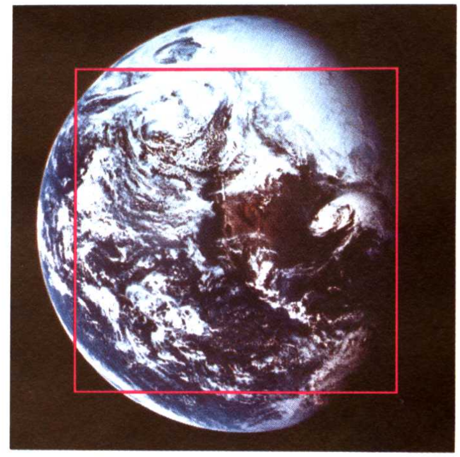


Figure 1–6 10,000 km = 10^7 m

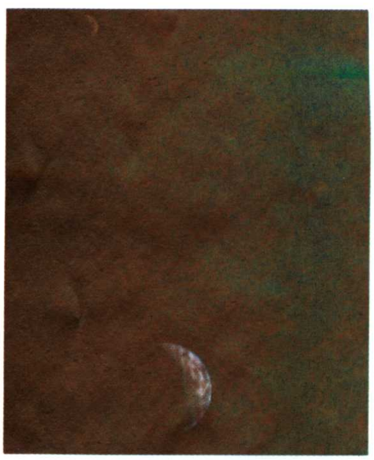


Figure 1–7 1,000,000 km = 10^9 m = 3 lt sec

When we have receded 100 times farther, we see a square 100 times larger in diameter: 1 million kilometers across. It encloses the orbit of the Moon around the Earth (Fig. 1–7). We can measure with our wristwatches the amount of time that it takes light to travel this distance. If we were carrying on a conversation by radio with someone at this distance, there would be pauses of noticeable length after we finished speaking before we heard an answer. These pauses occur because radio waves, even at the speed of light, take that amount of time to travel. Laser pulses from Earth that are bounced off the Moon to find the distance to the Moon (Appendices 2 and 4) take a noticeable time to return. This photograph was taken by the Voyager 1 spacecraft en route to Jupiter and Saturn. Because the Moon is many times fainter than the Earth, it was artificially brightened in the computer by a factor of three so that it would show up better in this print.

When we look on from 100 times farther away still, we see an area 100 million kilometers across, ⅔ the distance from the Earth to the Sun. We can now see the Sun and the two innermost planets in our field of view (Fig. 1–8).

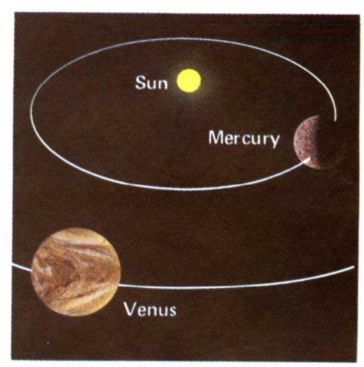


Figure 1–8 10^{11} m = 5 lt min

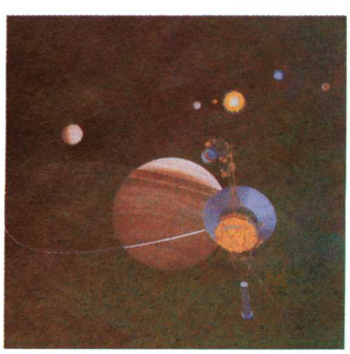


Figure 1–9 10^{13} m = 8 lt hrs

An area 10 billion kilometers across shows us the entire solar system in good perspective. It takes light 8 hours to travel this distance. The outer planets have become visible and are receding into the distance as our journey outward continues (Fig. 1–9). Our spacecraft have now visited or passed the Moon, Mercury, Venus, Mars, Jupiter, Saturn, Uranus, Neptune, and their moons; the results will be discussed at length in Part II. This artist's conception shows a Voyager spacecraft near Saturn.

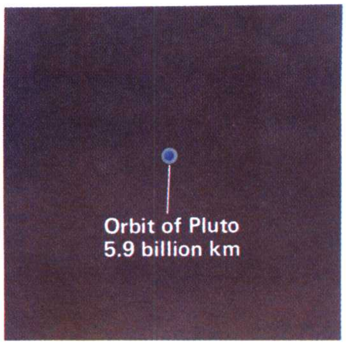


Figure 1–10 10^{15} m = 38 lt days

From 100 times farther away, we see little that is new. The solar system seems smaller, and we see the vastness of the empty space around us. We have not yet reached the scale at which another star besides the Sun is in a cube of this size (Fig. 1–10).

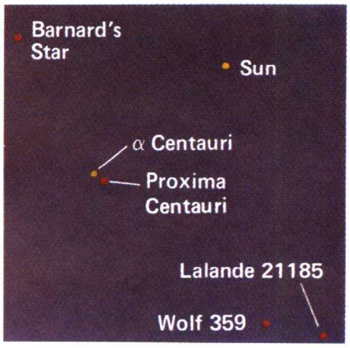


Figure 1–11 10^{17} m = 10 ly

As we continue to recede from the solar system, the nearest stars finally come into view. We are seeing an area 10 light years across, which contains only a few stars (Fig. 1–11), most of whose names are unfamiliar (Appendix 7). Part III of this book discusses the properties of the stars.

Figure 1–12 10^{19} m = 10^{3} ly

By the time we are 100 times farther away, we can see a fragment of our galaxy, the Milky Way Galaxy (Fig. 1–12). We see not only many individual stars but also many clusters of stars and many areas of glowing, reflecting, or opaque gas or dust called nebulae. Between the stars, there is a lot of material (most of which is invisible to our eyes) that can be studied with radio telescopes on Earth or in infrared, ultraviolet, or x-rays with telescopes in space. Part V of this book is devoted to the study of our galaxy and its contents. In this view we are looking past Halley's Comet to see the Milky Way.

In a field of view 100 times larger in diameter, we can now see an entire galaxy. The photograph (Fig. 1–13) shows the galaxy called M33, located in the direction of the constellation Triangulum, though it is far beyond the stars in that constellation. This galaxy shows arms wound in spiral form. The galaxy in which we live also has spiral arms, though they are wound more tightly.

Figure 1–13 10^{21} m = 10^{5} ly

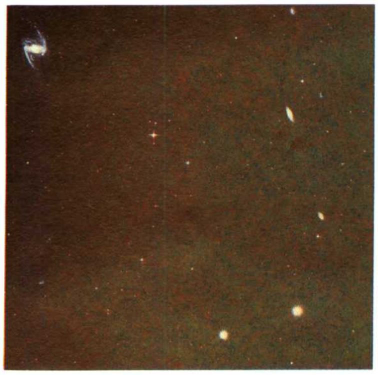


Figure 1–14 10^{23} m = 10^{7} ly

Next we move sufficiently far away so that we can see an area 10 million light years across (Fig. 1–14). There are 10^{25} centimeters in 10 million light years, about as many centimeters as there are grains of sand in all the beaches of the Earth. Our galaxy is in a cluster of galaxies, called the Local Group, that would take up only ⅓ of our angle of vision. In this group are all types of galaxies, which we will discuss in Chapter 31. The photograph shows part of a cluster of galaxies seen in the constellation Fornax but lying far beyond the stars in it.