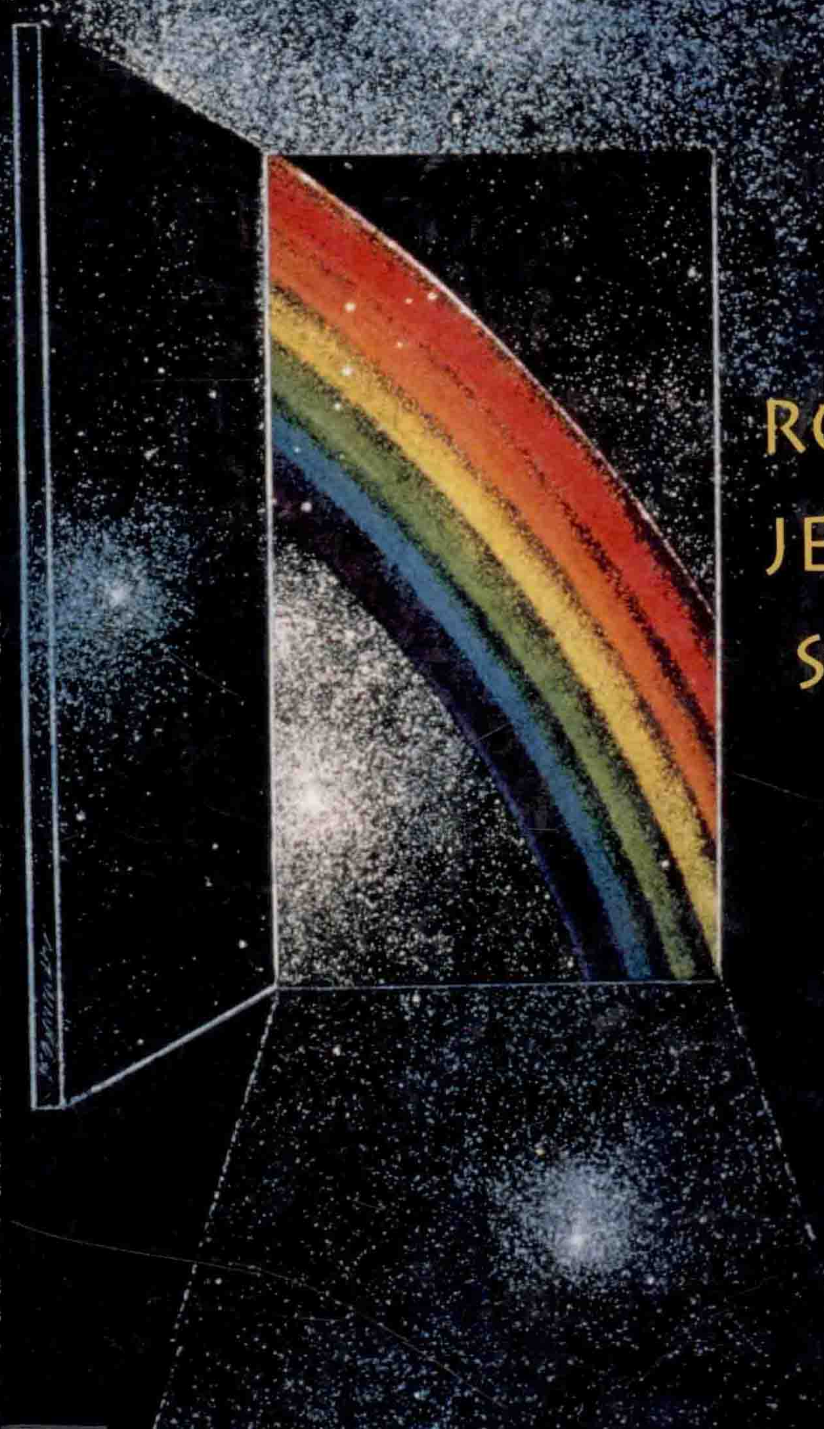
THIRD EDITION

DISCOVERING ASTRONOMY



ROBBINS
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JEFFERYS
·
SHAWL

DISCOVERING ASTRONOMY

THIRD EDITION

R. ROBERT ROBBINS
UNIVERSITY OF TEXAS, AUSTIN

WILLIAM H. JEFFERYS
UNIVERSITY OF TEXAS, AUSTIN

STEPHEN J. SHAWL
UNIVERSITY OF KANSAS

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ABOUT THE AUTHORS

R. Robert Robbins studied mathematics at Yale University and received his doctorate in astronomy from the University of California at Berkeley in 1966. He spent a year as a McDonald Observatory Fellow and a year at the University of Houston before joining the faculty at the University of Texas. His research interests have been in the fields of gaseous nebulae, atomic physics, and the transfer of radiation through gaseous media. In recent years his research interests have been turning towards archaeoastronomy and ethnoastronomy—in particular, studying the astronomy we can find in the structures and folklore of the Indians of Middle America and the American Southwest. He has received a variety of awards for excellence in teaching at the University of Texas and has served on a variety of national and international committees concerned with astronomy education. He has taught a variety of Chautauqua courses for college teachers, the most recent ones dealing with Mayan astronomy.

William H. Jefferys was educated at Wesleyan University and Yale University, receiving the Ph.D. degree from Yale in 1965. He has taught at Wesleyan University and at the University of Texas and is currently the Harlan J. Smith Centennial Professor in Astronomy at the University of Texas at Austin. His main research interests are in the fields of dynamical astronomy (the study of motions of planets, stars, and galaxies), astrometry (the measurement of the positions, orbits, and distances of celestial objects) and statistics. Since 1977 he has been the Astrometry Science Team Leader for the Hubble Space Telescope project. He has taught widely, both at the undergraduate and graduate levels, as well as teaching several National Science Foundation Chautauqua courses on teaching techniques to in-service teachers at both the high school and college levels . He believes strongly in the "hands on" approach to teaching that gives students a direct experience of what it is like to make, analyze, and understand scientific observations.

Stephen J. Shawl was educated at the University of California at Berkeley in the early 1960s and the University of Texas at Austin, where he received his Ph.D. in 1972. He has been teaching all levels of undergraduate astronomy since that time. His research interests have involved the study of the fundamental properties of globular star clusters, the presence of gas and dust in these clusters, and cool variable stars whose light is sometimes polarized. He has attended numerous National Science Foundation Chautauqua short courses for college teachers, the first one having been taught by Robbins and Jefferys. Because he was one of the original reviewers of the manuscript for *Discovering Astronomy*, he is especially pleased now to be a coauthor of this text. He has been a member of the Education Advisory Board of the American Astronomical Society (AAS) and is currently editor of the newsletter of the Working Group on Astronomy Education for the AAS.

PREFACE

The beauty of the night sky can be overwhelming. That beauty becomes even more inspiring when you have some understanding of what you are observing. When you see how humans approach an understanding of the universe, you begin to appreciate humanity and nature even more. The overall goal of this text, then, is to provide the reader with the opportunity to understand and appreciate the incredible place in which we exist.

The authors of this book feel that astronomy is not only an exciting and interesting subject, but also a living one in which everyone can directly participate. A considerable amount of astronomy can be experienced personally, and many things can be learned by simple and direct observations. We believe that the introductory survey course in astronomy, for which this book has been written, can be greatly enriched by the addition of observational activities that lead to a direct experience of the reader's universe. Such an approach, pioneered in astronomy by the first edition of *Discovering Astronomy*, reflects current discussions of science education at the national level. The idea of personal involvement is the guiding philosophy behind this book.

THE PROCESS OF SCIENCE

Science can be defined as a process followed by humans involved in a search for an understanding of their surroundings. This understanding is usually expressed in terms of theories whose predictions are verified or falsified by comparison with observation and experiment. The authors believe that an understanding of the scientific enterprise is important for people in a democratic society. For this reason, we do not present only the final results of scientific investigation, but we emphasize the process, which often contains false starts, side roads, and errors along the way to our current understanding, which will also undergo modification and refinement by future generations of scientists. In placing an emphasis on process, students are better positioned to understand discussions on which they will be asked to make informed decisions.

To help the student better understand the process of science, the book takes a discovery approach, which we discuss next.

THE DISCOVERY APPROACH

We have written this book as a comprehensive introductory astronomy text to facilitate unassisted inquiry through active observational experiences for students. Our approach is a discovery- or inquiry-based approach. To translate this philosophy into a unique textbook, we have woven observational and non-observational activities into the text at appropriate locations. There are two kinds of activities — (1) those included in the text and (2) those presented in a separate *Activity Kit* — allowing for a variety of teaching modes. Both are highlighted by colored boxes at pertinent places in the text narrative. Readers not doing the activities (or not possessing the kit) may simply continue with no loss of information or flow. Thus the book can be used effectively with or without the activities and discoveries.

DISCOVERIES

The Discovery Activities are designed to emphasize that the nature of science is one of discovery. Short and simple, these activities include instructions and inquiry questions. An example is the activity on Weightlessness in Chapter 5. They are noted at the appropriate place in the narrative and appear at the end of chapters.

KIT ACTIVITIES

Some observational activities require the student to make simple astronomical measurements using instruments such as a quadrant, cross-staff, spectrometer, or telescope. These die-cut instruments are included in a separate *Activity Kit* along with a manual of instructions for the activities. Also included are lenses, a holographic diffraction grating, and two pieces of polarizing filter. The *Activity Manual* also includes some stereoscopic images to enhance enjoyment and understanding of planetary bodies; two-color stereo viewers are also part of the Kit. An observational kit activity may require a student to measure, for example, planetary positions, average the measurements, and discuss the errors of the measurements. Other activities, such as Classification of Galaxy Types from Sky Survey Photographs, do not require measurement but the use of photographs (or in other cases, data) that are also included in the Kit.

The *Activity Kit*, with instruments and manual, is available from the publisher along with this text and can be ordered by your college bookstore. The kit can also be ordered separately from the text.

The activities and discoveries allow participation in astronomical exploration. They can be carried out by the thoughtful reader with no extra equipment or tutorial assistance.

PEDAGOGICAL STRUCTURE

We have implemented our inquiry-based approach in the pedagogical structure of this book. We have taken every opportunity to emphasize the scientific process and encourage observational activities to add to student understanding and enjoyment.

INQUIRIES

Each chapter contains in-chapter questions, which we call *Inquiries*, to emphasize the inquiry nature of the presentation. Placing these Inquiries within the text asks students to stop and think to themselves, "I just read something important; what was it?" Sometimes, the Inquiry asks the student to use the knowledge already gained and to think about some idea immediately prior to its discussion in the text. In this way, the student is actively participating, not just reading passively. The answers to all Inquiries are provided at the end of each chapter.

CHAPTER SUMMARIES

A new style of Chapter Summary has been developed to emphasize the nature of the scientific method. When appropriate, Chapter Summaries have three subsections: *Observations*, *Theory*, and *Conclusions*. Although many aspects of science belong in more than one category, this structure nevertheless serves to focus student attention onto these fundamental parts of the scientific method.

SUMMARY QUESTIONS

Next are Summary Questions, which ask students straightforward questions about the concepts covered in the chapter. These questions can serve as a review.

APPLYING YOUR KNOWLEDGE

Knowledge should be applied to new and different situations. This section, at the end of each chapter, presents the reader with questions meant to require the application of concepts previously learned. Some, marked by a bullet (■) require the use of simple mathematics.

GLOSSARY AND SCIENTIFIC APPENDICES

The book contains an extensive Glossary of those terms highlighted with bold print in the text. A set of appendices (A-G) presents a review of scientific notation as well as other mathematical concepts deemed unnecessary in the main text but important for complete understanding, as well as further data on planets, satellites, stars, and galaxies.

COLORFUL AND INSTRUCTIVE ILLUSTRATIONS

The art program includes full color photographs throughout to enable students to enjoy and appreciate the beauty of the universe better. Computer generated color diagrams help to clarify complex concepts. In so far as possible within the limits of space, diagrams convey single concepts.

ORGANIZATION

We have organized the book in the way astronomy developed: from observations to an understanding first of the solar system and only later to stars and galaxies. In this standard "inside out" approach, we have divided the book into five parts:

I. Discovering the Science of Astronomy
II. Discovering the Nature and Evolution of the Solar System
III. Discovering the Techniques of Astronomy
IV. Discovering the Nature and Evolution of Stars
V. Discovering the Nature and Evolution of Galaxies and the Universe

PHYSICS PRESENTED ONLY AS NEEDED

Within our organizational structure, the observational basis of astronomy is further emphasized by generally having observation precede theory. Furthermore, we present physical ideas where and when they are needed rather than grouping them together in a single chapter. This approach allows students to see a reason why physics is being presented, and they immediately see applications for the ideas. We have purposely placed the solar system before the chapters on radiation and telescopes for two reasons: (1) to get the student into modern astronomy as soon as possible without their feeling bogged down by physics ("if I had wanted a physics course I would have taken one!"), and (2) because much of a modern survey of our knowledge of the solar system at the introductory level may be presented effectively without prior knowledge of the material on light, spectra, and telescopes. Instructors desiring to discuss electromagnetic radiation first may do so without difficulty.

There are a few sections, noted with an asterisk, that some reviewers felt went beyond what was necessary for basic knowledge but the authors felt added to overall understanding. Such sections can be skipped if the instructor desires.

Science versus Pseudoscience

We believe that the ideas of what distinguishes science from pseudoscience are so important, our Chapter 2 on Science and Pseudoscience comes immediately after the book's introduction to astronomy. In this way, time constraints at the semester's end will not cause it to be skipped.

Comparative Planetology

Part II, on the nature and evolution of the solar system, begins with an overview of observations important to understanding the solar sysem. We then examine both early and modern hypotheses concerning the origin of the solar system. The next logical topic is a study of objects that are mostly unchanged since their formation and that provide astronomers with important information about the conditions at the formation time—comets, asteroids and meteoroids. Instructors preferring to discuss these objects after the planets may do so without loss of continuity.

The discussion of the planets has been completely rewritten and modernized. Chapter 8 on Earth and Moon presents those concepts necessary to understand the other planets and satellites in the solar system. Chapter 9 discusses the terrestrial planets, and Chapter 10 presents the Jovian planets and Pluto. The presentation within the chapters on the Earth-like and Jupiter-like planets differs from those in other books by approaching planets from the view of comparative planetology. Information about the planets is not isolated from comparable information on similar planets but is integrated together. "The Planets One by One," located after each of the terrestrial and Jovian planet chapters, summarize the information on each planet individually.

Logical Coverage of Stellar Evolution

The Sun is discussed in its role as a typical star at the point where the stellar evolution discussion begins (Part IV). Those instructors preferring to relate the Sun more closely to the solar system than to the stars can easily do so.

Following the discussion of the concepts required for understanding stellar evolution are chapters on star formation and evolution to the main sequence, post main-sequence evolution, and the terminal evolutionary events.

Interstellar Medium Covered as Needed

Rather than presenting the interstellar medium in isolation in a separate chapter, we consider it in various places as appropriate. For example, some information on nebulae is given as an example of spectra in Chapter 13. Additional discussion occurs in Chapter 17 on star formation. Finally, the effects of interstellar material on observations of stars and its influence on our knowledge of the structure of the Milky Way comes in Chapter 20.

SUPPLEMENTS

In order to enhance instructor's teaching resources, a comprehensive set of supplements accompanies *Discovering Astronomy*. For more information about these supplements, please contact your local Wiley representative. These supplements include:

- An *Instructor's Manual*, by Stephen J. Shawl. This manual has been prepared to provide instructors with teaching hints, syllabi, and chapter overviews for effective classroom use of *Discovering Astronomy*.
- *Student Study Guide*, by R. Robert Robbins, is available through him at Astronomy Department, University of Texas at Austin, Austin TX 78712. Internet address: rrr@astro.as.utexas.edu. This study guide was designed for instructors who are interested in assembling a self-paced, Keller-method course of instruction for their students. It can be used with small classes or with large ones such as that at the University of Texas that serves some 700 students per year.
- A *Test Bank*, prepared by Stephen J. Shawl, provides instructors with over eight hundred questions of various types. A *Computerized Test Bank* is also available for both Macintosh and PC platforms.
- 100 *Overhead Transparencies* replicate pedagogically useful line art from Wiley's astronomy archives.
- 100 *Slides* astronomical photographs enhance instructor's classroom capabilities.
- A *CD-ROM* containing line art, photographs, Concept Development Images (developed by Dr. Francis Lestingi at SUNY-Buffalo), and selected animations

from Wiley's acclaimed *Cosmic Clips* video permits professors to display a number of different images in the classroom. The CD-ROM is available for both Macintosh and PC platforms.

ACKNOWLEDGMENTS

The size of the supporting cast in making this book, or for that matter any book, possible is surprisingly large.

A large number of astronomers provided input, beginning with detailed reviews of the second edition, various intermediate drafts, and finally the one that went to press. They all helped to remove the many unnecessary errors that somehow seem to creep into a budding manuscript. Their help is warmly and gratefully acknowledged.

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R. ROBERT ROBBINS
(rrr@astro.as.utexas.edu)

WILLIAM H. JEFFERYS
(Bill@clyde.as.utexas.edu)

STEPHEN J. SHAWL
(shawl@Kuphsx.phsx.ukans.edu)

HELPFUL STUDY AIDS

5

THE HISTORICAL QUEST TO MODEL THE SOLAR SYSTEM

The progress of science is generally regarded as a kind of clean, rational advance along a straight line; in fact it has followed a zig-zag course, at times almost more bewildering than the evolution of political thought. The history of cosmic theories, in particular, may without exaggeration be called a history of collective obsessions and controlled schizophrenias; and the manner in which some of the most important individual discoveries were arrived at reminds one more of a sleepwalker's performance than an electronic brain.

ARTHUR KOESTLER, *THE SLEEPWALKERS*, 1959

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OPENING QUOTE

Each chapter opens with a quotation from popular fiction or a scientific source that helps to set the stage for topics covered in the chapter. These quotes often give a perspective from outside the immediate field of astronomy.

CHAPTER OVERVIEW

A brief paragraph gives an overview of concepts discussed in the chapter. It serves as an organizing device to help you preview chapter coverage.

5.1
GREEK ASTRONOMY

In this chapter we follow the development of our understanding of our own corner of the universe, the solar system. We will not seek to be comprehensive or encyclopedic in our historical coverage. Instead, we will be more interested in how the ideas that developed in one era were a natural outgrowth of the state of astronomical observations and degree of sophistication of the times. In previous chapters we briefly discussed some historical aspects of astronomy; for example, we considered the notion of a round Earth, and how this concept slowly came to be accepted by Greek thinkers through the gradual accumulation of evidence from both terrestrial and astronomical observations. Yet this concept was established relatively rapidly when compared to the slow acceptance of the idea of a Sun-centered solar system.

5.1
GREEK ASTRONOMY

While we saw in the last chapter that a variety of cultures were intimately involved with phenomena of the sky, it was Greek culture that made progress toward the models we have today. We now look more closely at the astronomical contributions of Greek culture.

WHAT THE GREEKS INHERITED

The Babylonians and Egyptians, who for several thousand years kept records that contained much potentially valuable information, bequeathed to the Greeks an extensive body of astronomical knowledge. However, the astronomy of both Egypt and Babylonia was the province of a priestly aristocracy; as a consequence, practical and political considerations often took precedence over theoretical inquiries. Egyptian astronomers, for example, had discovered that when the bright star Sirius could just be seen rising in the east before the Sun, the flooding of the Nile was imminent. Such knowledge gave tremendous power to the priesthood and inevitably involved its members closely with the state. Similarly, in Babylonia, astronomer-priests had acquired a considerable amount of information concerning the motions of the Moon, Sun, and planets and had found certain regularly occurring cycles that enabled them to predict some eclipses, a power that was frequently used for political purposes.

The Egyptians and Babylonians knew the length of the year and the different types of calendars, both solar and lunar. The Egyptians had learned the rudiments of simple mathematics, algebra, and geometry. Sundials had been invented, and systems of timekeeping were in existence. The Babylonians had made systematic observations of the positions of heavenly bodies and had practical methods for predicting the positions of the Moon, Sun, and planets. **Figure 5–1**, for example, shows a table of data for Jupiter. The bottom part of the figure describes the method of calculation. The Babylonian value for the length of the month was not surpassed in accuracy until the end of the nineteenth century. Both cultures had attempted to construct a cosmology that placed Earth and humanity in their proper position relative to the universe and the gods, but they never attempted to construct a truly consistent theoretical framework for their cosmology in the way the Greeks did.

FIGURE 5–1. A clay tablet from ancient Mesopotamia containing astronomical observations of Jupiter in the top part, and a description of the method of calculation in the bottom part.

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5.1
GREEK ASTRONOMY

FIGURE 5–4. Two objects with the same angular sizes have diameters that are proportional to their distances.

Inquiry 5–3 Aristarchus was the first to propose that the Earth goes around the Sun, rather than vice versa. Suggest one factor that may have led him to this conclusion.

Eratosthenes

Another classic experiment of antiquity was the determination of the Earth's circumference by **Eratosthenes** (c. 200 B.C.). The conclusions of Aristarchus concerning the relative sizes and distances of the Earth, Moon, and Sun were all in terms of the then unknown size of the Earth. Their sizes in customary units (the Greeks used a unit of length called the *stadium*) could not be known until the Earth's size was known.

Eratosthenes had heard that at Syene, near the modern Aswan in Egypt, there was a deep well, and that on a certain day of the year the Sun stood directly overhead so that its reflection could be seen in the bottom of the well. Eratosthenes was also able to observe that on that same day of the year in Alexandria, where he lived, the Sun was not directly overhead but was 7° south of the zenith. He determined this angle with a gnomon, just as

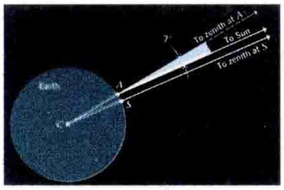

FIGURE 5–5. Eratosthenes' measurement of the diameter of the Earth. The difference in altitude of the Sun is proportional to the distance between the two points, which is known. This allows the length of one degree on the Earth's surface to be determined.

you may have done in Kit Activity 4–3. **Figure 5–5** shows the geometry of Eratosthenes' experiment. Point *A* represents Alexandria and point *S* is Syene; point *C* is at the center of the Earth. The Sun is so far away that the lines *A*-Sun and *S*-Sun are nearly parallel. The angle at *A* is nearly equal to the angle at *C* at the center of the Earth, and we may write the following proportion:

$$\frac{\text{circumference of Earth}}{\text{distance from } A \text{ to } S} = \frac{360°}{\text{angle at } C}.$$

Inquiry 5–4 Assuming that the angle at *C* is 7° and that the distance of Alexandria from Syene is 5000 stadia, what is the diameter of the Earth in stadia? (Stadia is the plural of stadium.) Although the exact length of a stadium is unknown, compute the radius of the Earth assuming it to be about one-tenth of a mile.

Inquiry 5–5 What does Eratosthenes' experiment assume about the shape of the Earth?

Inquiry 5–6 If the Earth were flat, what would be the value of the angle at *C*?

Hipparchus

Perhaps the greatest of all ancient astronomers was **Hipparchus** (c. 150 B.C.). Many of the conclusions he drew were so sophisticated that it takes some knowledge of astronomy to appreciate how great his contributions were. He built an observatory, constructed the best astronomical instruments up to that time, and established a program of careful and systematic observations that resulted in the compilation of a great star catalog, with 850 entries, using a celestial coordinate system similar to our modern one for cataloging the sky. It was Hipparchus who originated a system, which is still in use today in modified form, for estimating the brightness of stars. In addition, he paid much attention to the older Egyptian observations and detected long-term trends in the motions of the celestial sphere that had been previously unsuspected. He deduced Earth's precession, which is so slow that it takes almost 26,000 years for it to complete one cycle. Finally, he greatly developed trigonometry, which was, and still is, a useful tool for astronomy.

Other Deductions of the Greek Astronomers: The Distances of the Planets

The Greeks estimated the relative distances of the planets from Earth, by means of principles still in use today for determining distances to astronomical objects. They reasoned that the more distant a planet was, the more

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INQUIRIES

Throughout the text, Inquiries (questions) are included in appropriate places to ask you to use the information presented in the text. By actively participating and not just passively reading, you gain understanding of the concepts. Answers to all Inquiries are presented at the end of each chapter.

CHAPTER 5
THE HISTORICAL QUEST TO MODEL THE SOLAR SYSTEM

owly it would move across the sky. The effect is simi- r to what happens when we compare the apparent otion of a high-flying airplane with that of one that is ying very low. The distant airplane appears to move slowly across the sky, whereas the low-flying one is seen for only a short time and then is gone. In the same way, the Greeks could put most of the naked-eye planets in order of their distance from Earth by assuming that increasing distances corresponded to slower motions. The argument fails with Mercury and Venus, however, because it places Mercury closer to Earth.

Inquiry 5–7 What assumptions are made in employing this argument?

We can obtain another, independent determination of relative planetary distances from their brightnesses. We use an analogy: when you are driving at night and wish to pass the car in front of yours, you pass only if the headlights of the oncoming car are faint. When you do this, you are making an implicit assumption: all car headlights have about the same intrinsic brightness, with their apparent brightness depending on the distance. Similarly, if we assume that all planets have the same intrinsic brightness, then their apparent brightness as seen from Earth would depend on their distances from us. Of course, all the planets do not have the same intrinsic brightness, because their differences in size and distance from the Sun, combined with differences in surface and atmospheric properties, affect the amount of light they reflect in our direction. However, even allowing for these uncertainties, it is still possible to use this principle to rank the planets approximately in order of distance from the Earth.

The Apparent Motions of the Planets Relative to the Stars

Three additional observations of planetary motion were important in determining the details of the models the Greeks developed. These observations, which played a prominent role in their models, are:

1. Because the planets are considerably closer to us than the fixed stars, they appear to move against the starry background. Observations of Mars, Jupiter, and Saturn showed them to move generally eastward on the celestial sphere.
2. Occasionally, however, as discussed in Chapter 4, a planet's motion changes from eastward to westward. This retrograde motion would persist for up to several months but would cease as the planet's motion slowed down and again reversed its direction, resuming its normal easterly motion (see Figure 4–28).
3. Venus and Mercury are never more than 48° and 28°, respectively, from the Sun.

The Geocentric Model of the Solar System

To describe the observed planetary motions, it was necessary to decide where the center of the system should be. There were really only two obvious candidates—Earth and the Sun. This question was considered carefully by Greek philosophers, and the fact that ultimately they reached an incorrect conclusion provides an interesting example of why the scientific method is not the simple turn-the-crank-and-the-answers-fall-out process that some sources describe it to be. If the Sun is in the center of the solar system, then Earth moves around it in space. Such a hypothesis provides a prediction. As shown in **Figure 5–6**, some of the stars ought to shift their apparent positions in the sky as the Earth moves from one side of its orbit to the other. Such **parallax** effects, as they are called, were looked for by many Greek observers, including Hipparchus, but were never found. The Greeks therefore concluded that the Earth was stationary in space.

Aristarchus, however, apparently espoused the theory that the Earth orbits the Sun, if surviving works of Archimedes and Plutarch are correct. Unfortunately, the work in which he put forth his hypothesis is lost, and apparently no other Greek astronomers held to this opinion. The model of a **geocentric** (Earth-centered)

INSTRUCTIVE ILLUSTRATIONS

Computer-generated color diagrams help to clarify complex concepts and encourage an appreciation of the beauty of the universe.

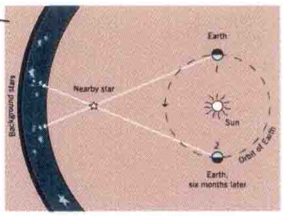

FIGURE 5–6. Stellar parallax. The apparent position of a star with respect to the background stars appears to change as the Earth goes around the Sun. (Not to scale.)

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Inquiry 5–19 If the distance between mass M_1 and mass M_2 is made four times *greater*, by what factor is the gravitational force between them changed? Is it increased or decreased?

While the idea that bodies of different masses fall at the same rate was experimentally shown by Galileo to be true, its truth does not make sense to most people. Its validity is shown in Appendix A7.

It is a measure of Newton's genius that he proposed that his laws of motion and gravity applied not only to objects on Earth but to all bodies in the universe. One of the first things he did was to compare the force of gravity exerted by the Earth on a body, allegedly a falling apple, with the gravitational force that would be required to keep the Moon in its orbit around the Earth. As shown in **Figure 5–21**, if there were no gravitational force exerted by the Earth on the Moon, it would travel in a straight line past the Earth in accordance with Newton's first law. To make the Moon travel around the Earth requires a force toward the Earth. The Earth's gravitational force on the Moon causes it to deviate from a straight line and follow a curved path around the Earth. For each kilometer the Moon moves in its orbit, the Moon must fall 0.14 cm towards the Earth's surface in order to stay in its elliptical orbit. Because of the curvature of the Earth's surface, the distance of the Moon from the Earth remains constant. In other words, the Earth's force of gravity causes the Moon to accelerate just enough to maintain its constant distance above the Earth's surface. For this reason, the Moon's orbital motion can be described as resulting from the Moon's falling toward's the Earth's center! From such considerations Newton found that the actual force required to keep the Moon in its orbit around the Earth agreed well with the value he computed theoretically.

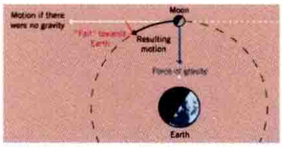

FIGURE 5–21. The motion of the Moon around the Earth according to Newton. The Moon "falls" toward the Earth just enough to keep it on a curved elliptical path around the planet.

Weight

Weight is the force a gravitating body exerts on another mass. In particular, your weight is the gravitational force exerted by the Earth's mass on your body. Your weight depends on the mass of your body, the mass of the Earth, and your distance from the Earth's center, which is the Earth's radius. For this reason, your weight would be different should you travel to a different planet having a different mass and size than the Earth; your mass, however, would be the same. Interested readers can find weight expressed mathematically in Appendix A8.

TO UNDERSTAND WHY AN ASTRONAUT IS WEIGHTLESS EVEN THOUGH THERE IS STILL GRAVITY IN SPACE, YOU SHOULD DO DISCOVERY 5–1 AT THIS TIME.

Momentum

You probably have some intuitive feel for the word **momentum**. A train moving at 20 miles per hour has more momentum than a bicycle moving at the same speed; it would have more impact and effect if it ran into something! For a body moving in a straight line, **linear momentum** is defined as the body's mass times its velocity.

Newton's first law can also be expressed as the principle of the **conservation of linear momentum**. This says that for an isolated system of bodies the sum of the linear momenta of all bodies in a system is always the same. If some bodies in a group slow down, others must speed up by a corresponding amount.

Most bodies move in curved paths, and the concept of **angular momentum** comes into play. The amount of angular momentum possessed by a planet in a *circular* orbit around the Sun is defined by

angular momentum = mass × speed × distance from planet to Sun.

Expressed symbolically, if M is the mass of a body and v its speed when at a distance r, the angular momentum is given by

$$\textit{angular momentum} = Mvr.$$

Like linear momentum, angular momentum is also conserved for isolated systems. If the mass of an orbiting planet remains constant, the only way for angular momentum to remain constant is for the speed of the planet to increase as the distance decreases, and vice versa. This is exactly what Kepler's second law says. The concept of conservation of angular momentum is important in understanding not only the motions of planets but also such diverse subjects as the formation of the

REFERENCES TO DISCOVERY ACTIVITIES

Although Discoveries appear at the end of the chapter so as not to disrupt the flow of reading, they are referenced at the appropriate places in a blue shaded notation. [It is not necessary to do these activities to understand the concepts.]

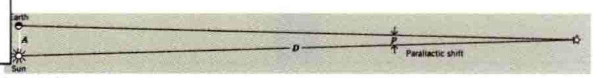

FIGURE 5–25. The relationship between the distance of a star and its parallax. The greater the distance, the smaller the parallax angle.

tant than the nearby stars, the angle *A*-star-*B* of Figure 5–24*a* will be practically equal to the angular shift in position shown in Figure 5–24*b*.

How large a distance to the stars does the small observed parallax imply? Consider the right triangle formed by the Earth, the Sun, and a nearby star, as shown in **Figure 5–25**. The side labeled A is the distance from the Earth to the Sun, which is of course 1 AU. The angle p is called the **parallax** of the star; it is one-half the total parallactic shift shown in Figure 5–24*a*. Because the triangle is so long and skinny, the distance D from the Sun to the star can be computed from the angular size formula used in Chapter 3, namely,

$$D = 57.3° \times \frac{A}{p}$$

if the parallax p is expressed in degrees. (We have replaced the variable R used in Chapter 3 with the distance D.) For example, the nearest star to the Earth, Proxima Centauri, has a measured parallax of 0.76", which corresponds to 0.00021 degrees, an extremely small angle. Substituting this angle and the length of an astronomical unit, in kilometers, into the formula, we find the distance to be

$$\begin{aligned} D &= 57.3 \times \frac{150{,}000{,}000 \text{ km}}{0.00021} \\ &= 41{,}000{,}000{,}000{,}000 \text{ km} \\ &= 4.1 \times 10^{13} \text{ km}. \end{aligned}$$

Kilometers or miles are clearly not an appropriate unit for measuring distances to stars. Nor are astronomical units; the distance to Proxima Centauri is over 270,000 AU, for example. Just as we describe distances around town in miles or kilometers rather than inches or centimeters, we describe distances to stars in units that are large enough so that the numbers we use have convenient sizes. This is why we use light-years, because one light-year is about 9.5×10^{12} km or 5.9×10^{12} miles. The distance of Proxima Centauri, then, is 4.3 ly.

READERS HAVING THE ACTIVITY KIT SHOULD DO KIT ACTIVITY 5–1 (A PARALLAX MEASUREMENT) AT THIS TIME.

5.7 OBSERVATIONAL EVIDENCE OF THE EARTH'S ROTATION

While every schoolchild can tell you the Earth rotates, few college graduates can explain *how* we know this simplest of all astronomical facts. As evidence, most people would cite the observation of the Sun and stars rising in the east and setting in the west. If you were to suggest, just for argument, that the east-west motion of the Sun and stars is produced by the motion of crystalline spheres to which the Sun and stars are attached, great confusion would result.

Foucault Pendulum

A famous demonstration of the rotation of the Earth is the pendulum experiment first performed by the nineteenth-century French physicist Jean-Bernard-Léon Foucault. In this experiment, a massive pendulum is hung from a long wire and set in motion. Pegs placed in a circle around the pendulum are successively knocked down over time due to the apparently changing plane in which the pendulum swings. To construct the simplest possible explanation of what is observed, imagine that we suspend a pendulum on a long cable from a support that has been placed at the North Pole (Figure 5–26). We make the coupling between the cable

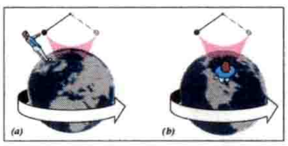

FIGURE 5–26. The Foucault pendulum. (*a*) Setup of the experiment. (*b*) Six hours later, the pendulum still vibrates in the same plane relative to the stars, but the observer has rotated.

REFERENCE TO KIT ACTIVITIES

Activities requiring measurement can be carried out using the Activity Kit available separately. The yellow shaded notation indicates the relevant place in the text for these activities to be performed. [It is not necessary to do these activities to understand the concepts.]

gion during the fall hurricane season. The low pressure in the center is surrounded by regions of high pressure, so winds blow in toward the center. As they do, they are deflected to the right, causing a counterclockwise circulation of wind inside the low pressure region (for Northern Hemisphere hurricanes). If such a disturbance were to move in from the Gulf of Mexico and locate its center of low pressure at the Texas-Louisiana border, central Texas would experience winds from the north, New Orleans would have winds from the south, and Little Rock, Arkansas, would have southeasterly winds.

FIGURE 5–28. Winds will push toward the center of a low-pressure storm region from the surrounding high-pressure regions. As they move, they will be deflected to the right (in the Northern Hemisphere) because of Coriolis effects. The net effect is to make the winds circulate in a counterclockwise direction around the center of the low-pressure region.

DISCOVERY 5–1 WEIGHTLESSNESS

When you have completed this Discovery, you should be able to do the following:

- Describe what is meant by weightlessness.

An astronaut floating in a space shuttle has mass but is weightless. Weightlessness does not occur, however, from a lack of gravity in space.

□ **Discovery Inquiry 5–1a** Suppose you were standing on a scale in a stopped elevator. What would happen to the scale reading when the elevator suddenly accelerates upward? What would happen to the scale reading when the elevator rapidly descends from rest?

Although the elevator has accelerated, the force of gravity on the elevator occupants has not changed. The scale reading, however, has changed because of the acceleration.

You can easily demonstrate weightlessness for yourself. Take a paper cup or an aluminum pop can and punch two holes on opposite sides near the bottom. With your fingers over the holes, fill the container with water.

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DISCOVERY ACTIVITIES

The nature of science is one of discovery. Short and simple Discovery Activities appear at the end of many chapters to reflect this emphasis by getting you actively involved with the material.

□ **Discovery Inquiry 5–1b** *Before removing your fingers from the holes,* describe what you expect to happen. Then, while taking necessary precautions, remove your fingers from the holes and observe what happens.

Again place your fingers over the holes and fill with water.

□ **Discovery Inquiry 5–1c** *Before dropping the container* (into a garbage can, the bath tub, or *safely* outside!), describe what you expect to observe. After thinking about the answer, drop the container from as high as you can reach, and describe what you observed.

In this experiment, you should have observed no water flowing from the container while it was dropping. Although gravity was still there, the water was weightless *with respect to the container* because the water and the container accelerated downward at the same rate. Similarly, because the astronaut and the space shuttle both accelerate towards the center of the Earth *at the same rate*, the astronaut is weightless.

DISCOVERY INQUIRIES

To reinforce the key concepts of these Discoveries, questions (Inquiries) are included to guide your thinking.

CHAPTER SUMMARY

The Chapter Summary not only reviews the topics covered but presents the information in a way that reflects the scientific method. The material is organized in subsections of Observations, Theory, and Conclusions to give you practice in thinking in these scientific ways.

CHAPTER SUMMARY

OBSERVATIONS

- **Aristarchus** first suggested that the Earth circles the Sun, and found the relative sizes of the Earth, Moon, and Sun, as well as the relative distances of the Moon and Sun. **Eratosthenes** first found the size of the Earth. **Hipparchus** made a great star catalog, began the magnitude system used to specify the brightness of stars, and discovered precession. **Ptolemy** advanced the theory of planetary epicycles and helped preserve Greek knowledge in the *Almagest*.
- The Greeks observed that the planets moved against the starry background; sometimes changed directions and moved with a **retrograde motion**; and, in the case of Mercury and Venus, were never far from the Sun.
- **Tycho Brahe** built large instruments and made observations over extended periods of time. **Johannes Kepler** found three empirical laws of planetary motion: (1) planets revolve about the Sun in elliptical orbits with the Sun at one focus; (2) planets move more rapidly when close to the Sun than when farther away; (3) if the period of a planet in its orbit is P years and the semi-major axis is A astronomical units, then $P^2 = A^3$.
- **Galileo** made the first telescopic observations and discovered that the Milky Way consists of a large number of stars. He observed lunar surface features, four Jovian satellites, sunspots, and phases of planets. He showed experimentally that objects of different masses fall to the ground with identical accelerations.
- The **aberration of starlight** is a small apparent shift in the direction to an object caused by the motion of an observer. The observation of this effect illustrates the motion of the Earth.
- **Stellar parallax** is the apparent change in the direction to an object caused by a change in position of an observer.
- The **Coriolis effect** is the apparent rightward drift of a projectile fired from the equator toward the North Pole, or from the North Pole toward the equator. It is caused by the fact that equatorial regions move more rapidly than polar regions.

THEORY

- Greek science and philosophy assumed that planets exhibit uniform motion in circular orbits.
- **Nicolas Copernicus** proposed the heliocentric hypothesis.
- **Mass** is a quantity that measures the amount of **inertia** that a body contains. A body's mass is independent of its location. **Velocity** is a change in location or direction of motion divided by the time over which the change occurs. **Acceleration** is a change in an object's velocity divided by the time over which the change occurs.

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CHAPTER 5
THE HISTORICAL QUEST TO MODEL THE SOLAR SYSTEM

- Newton's three laws describe how bodies move both in the absence and presense of forces. They are general laws applicable to a wide variety of situations.
- **The universal law of gravitation**, found by Newton, provided a means to connect the motion of the Moon with the motion of falling bodies on Earth.
- From Newton's laws, a modification of Kepler's third law results that allows astronomers to determine the masses of orbiting bodies:

$$(M_1 + M_2)P^2 = A^3.$$

- The amounts of **linear momentum** and **angular momentum** contained in an isolated system are both conserved.
- The **weight** of an object is determined by the gravitational force exerted on it by the Earth. The weight depends on the object's location.

Conclusions

- From observations made with the **Foucault pendulum**, astronomers infer the rotation of the Earth.
- From observations of the aberration of starlight, astronomers infer the revolution of the Earth about the Sun.
- Newton's laws provide a model that successfully explains past events and predicts future ones. From them, Kepler's laws of planetary motion can be derived.

SUMMARY QUESTIONS

1. What is the significance of the observations of Aristarchus, Eratosthenes, and Hipparchus? What are the principles used to make their measurements of the sizes of the Earth and Moon?
2. What are two methods by which the order of the planets from the Sun could be determined?
3. What planetary observations must a reasonable model of the solar system incorporate? In your answer use diagrams to show how the Ptolemaic and heliocentric hypotheses explain the observations.
4. What is meant by stellar parallax? Explain its cause. How can parallax be used to distinguish between heliocentric and geocentric hypotheses? Why did the Greeks not observe stellar parallax?
5. What role did the concept of uniform circular motion play in the history of astronomical thought? Give examples from several eras.
6. What were specific astronomical contributions made by Copernicus and Brahe? What was the importance of these contributions?
7. State and explain Kepler's three laws. Explain Kepler's second law in terms of the conservation of angular momentum.
8. What are the principal astronomical discoveries of Galileo? Explain how these discoveries may have accelerated the acceptance of the heliocentric hypothesis.
9. State Newton's laws of motion and the law of gravity. Explain how, in principle, they can be used to explain the orbiting of one body about another.
10. What are some specific astronomical examples of how Newton's laws have been shown to be valid descriptions of nature?
11. How were the heliocentric hypothesis and the Earth's rotation finally confirmed observationally? How did Newton's laws play a role in demonstrating the Earth's rotation and revolution?

APPLYING YOUR KNOWLEDGE

1. Make up a table that lists, chronologically, the contributions to astronomy made by Aristarchus, Apollonius, Eratosthenes, Hipparchus, Ptolemy, and Pythagoras. Include dates.
2. If you had been a traditional scholar in the mid-1500s, what arguments would you have presented *against* the Copernican system?
3. Of the following people, who in your opinion made the most important contribution to astronomy: Copernicus, Brahe, Kepler, Galileo, Newton? Explain.
4. Use the definition of acceleration to list the accelerators in a standard passenger car.
5. Use Newton's second law to explain why a planet in an elliptical orbit moves more rapidly when near the Sun than when farther away.
6. Explain why your weight would be different on Mars than it is on Earth.
7. Why can a rocket escape from the Moon's surface with a smaller speed than is needed to escape from the Earth's surface?

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SUMMARY QUESTIONS

Straightforward questions at the end of the chapter help you to review the material you have read and to check your understanding of it. Answering these questions is good practice for taking tests.

APPLYING YOUR KNOWLEDGE

The best way to test your comprehension of new material is to be able to apply this knowledge to new and different situations. These end-of-chapter questions are designed to require the application of concepts previously learned. Those questions requiring the use of simple mathematics are marked by a square bullet (■).

ANSWERS TO INQUIRIES

■ 8. What is the distance from the Sun to a planet whose period is 129.14 days?

■ 9. Find the ratio of the gravitational attraction between (*a*) a man of mass 100 kg and a woman of mass 50 kg who is 10 meters away from him, and (*b*) the attraction between the woman and the Earth. (Hint: See Appendix A8.)

■ 10. If the Sun is 2×10^9 AU from the center of the Milky Way, and if it has a period of 200 million years, what is the mass of the Milky Way galaxy?

■ 11. If identical galaxies at a distance of 650 million ly and having a mass of 10^{10} solar masses each were observed to have an angular separation of 10 seconds of arc, how long would their orbital period be? Assume the galaxies are seen at their maximum separation. (Hint: This problem contains a number of steps along the way.)

■ 12. How much would a 100-lb person weigh on the Moon? (Hint: Write an expression for the person's weight on Earth and an equivalent one for the Moon. Then divide one equation by the other; you will find that some quantities drop out of the problem.)

■ 13. How fast would a person of mass 50 kg (about 110 lbs) have to run to have the same linear momentum as a 5000-kg bus (about 5 tons) traveling 60 miles per hour?

■ 14. What would be the parallax of Proxima Centauri if it were observed from a telescope on one of Saturn's satellites?

ANSWERS TO INQUIRIES

5–1. Circular orbits and uniform motion.
5–2. The Earth is four times larger.
5–3. Because he knew the Moon was smaller than the Earth and was in orbit about the Earth, and because he now knew the Sun was farther than the Moon, it was logical that the Earth would go around the Sun.
5–4. 5000 stadia × 360°/7° = 260,000 stadia.
5–5. That it is perfectly spherical.
5–6. Zero degrees.
5–7. That the planets are moving at about the same speed, so their apparent speeds are due only to their respective distances. While the assumption is incorrect, the result ends up being correct.
5–8. Stars are very far away.
5–9. Only crescent phases would occur.
5–10. There are countless examples. Some are the germ model of disease, economic models used to set government fiscal policy, and educational models used to design instruction.
5–11. On a straight line, with the Earth in the middle.
5–12. Each has some points of simplicity. Ptolemy's has fewer epicycles, but Copernicus's has a neater explanation of retrograde motion, which in addition predicts retrograde motion only when it is actually observed.
5–13. About 1.87 years.
5–14. About 19.2 AU.
5–15. The planets are closer than stars.
5–16. Jupiter was clearly moving and dragging its moons along.
5–17. From $F = ma$, the can with more mass (the one filled with concrete) would have the smaller acceleration if the forces were equal.
5–18. The reaction force on the foot will certainly be felt more in the case of the concrete can.
5–19. The force is 16 times smaller.
5–20. Twice as great.
5–21. $(M_1 + M_2) = 8^3/10^2 = 512/100 = 5.1$ solar masses.
5–22. In the Southern Hemisphere, the pendulum would appear to rotate in the opposite direction from its rotation in the Northern Hemisphere. Therefore, for the direction of oscillation to change as the pendulum is carried from one hemisphere to the other, there must be no rotation at the equator.
5–23. In the Southern Hemisphere, projectiles will always deflect to the left, when fired any direction except directly east or west.
5–24. Yes. Imagining the ball of the pendulum to be a projectile deflecting to the right on each swing gives it the rotation we observe.

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ANSWERS TO INQUIRIES

As a check on how you are doing as you progress through the chapter, the answers to the periodic Inquiries are included at the end of the chapter.

BRIEF CONTENTS

CONTENTS

PART TWO

DISCOVERING THE NATURE AND EVOLUTION OF THE SOLAR SYSTEM

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