CONCEPTUAL ASTRONOMY

Michael Zeilik

ASTRONO

A Journey of Ideas

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Preface

Science is not about control. It is about cultivating a perpetual condition of wonder in the face of something that forever grows one step richer and subtler than our latest theory about it.

Richard Powers, The Gold Bug Variations

Students are fascinated by astronomy but frustrated in their study of it. In the United States, colleges and universities typically offer an introductory astronomy course for non-science majors—a course I will call "Astronomy 101." This course lasts but a semester and covers "all" of the universe, or at least selected pieces of it. The students taking this course are usually new to the university (and may well be older in age), and choose Astronomy 101 over other disciplines (such as physics!) that may also satisfy some form of a science requirement for graduation. At large universities, Astronomy 101 tends to be offered as a large lecture course with a few hundred students. Most of these students are novices, with little practical experience with science or much careful thought about it.

Novice students in all areas suffer two common problems. One, they lack concrete experience. Science seems especially hard to them because they have not done it themselves or observed scientists carrying it out. Hence, the students lack even the exposure to the intellectual framework and the practical aspects of "doing science." They tend to see science as completed rather than in process, frozen facts rather than a vital adventure. Two, they see lots of trees and rarely a forest. I am an astronomer because of the beauty of the unity of the universe. Students see this and that planet, this and that star, this and that galaxy—but have a hard time seeing how it all hangs together. Astronomy makes matters worse by being at such a distance; once we leave the solar system, it is hard to present astronomical objects concretely. This problem reinforces their preconception that science is a large bunch of unrelated "facts," which are memorized for exams and then quickly forgotten. The *Project 2061 Panel Report on Physical and Information Sciences and Engineering* of the American Association for the Advancement of Science addresses many of these issues in a concise way. Project 2061 has as its overarching goal the development of science literacy; the panel report specified the knowledge, skills, and attitudes students in science and engineering should acquire. It has shaped the structure of this book.

Less Is More: A Conceptual Approach

What to do? We should meet the needs of most of the students in Astronomy 101 while conveying to them the true nature of the scientific enterprise—and the beauty of the universe. I have evolved my teaching in a direction that attempts to grapple with the problems that baffle novice students. First, I have opted for "less is more" by covering less astronomical material. In particular, you will find very little in this book about the history of astronomy. Also, I have given scant attention to instrumentation; most of that is in Appendix H on Telescopes.

Second, I have tried to emphasize the conceptual story—how astronomers understand the universe by building models of its parts and pieces and also of the whole cosmos. The glue for the astronomical story is some essential physics, without which we have no connections. I believe you cannot teach introductory astronomy with any understanding unless you provide selected physical concepts in the proper context.

Third, I have made explicit the astronomical and physical concepts that provide the foundation to our understanding. The slant here is on the astrophysics rather than just the astronomy. My experience is that the many facts fog the concepts for novice students, so why not bring the concepts right out in front?

The story line revolves around 25 conceptual themes that are specified at the end of the Preface. For most of these, at least two sections are listed in which these themes come across most strongly. If any theme resounds the strongest, it is that about energy—its varied forms, fast and slow transformations, and careful conservation. The flow of heat from hotter to cooler regions marks an essential insight in understanding the functioning of the universe.

Specifying and Unifying Concepts

Conceptual Astronomy unfolds the concrete form of my philosophy. I have presented the concepts at many levels to help students see their interconnections. The book is split into three parts: Part 1, Concepts of the Solar System; Part 2, Concepts of Stellar Evolution; and Part 3, Concepts of Cosmology. Note that we start with the familiar (the earth and sky) and move to the more abstract (and generally more distant!) pieces of the universe. Each part deals with interrelated material. Each also begins with a statement of *Unifying Concepts* that ties the information together; their selection has been guided by the *Project 2061 Panel Report*.

Within the parts, each chapter starts with a *Central Concept* statement that aims to unify the material. Within the chapter, *Chapter Concepts* are identified by color bars. Now, some concepts are more powerful and more important than others; these appear in more than one chapter. So concepts appear explicitly at many levels in this book, just as they do in astronomy.

Integrating Concepts

How to help the student pull these concepts together into the big picture? Each chapter ends with a section called *The Larger View*. These are not intended to act as summaries; instead, I have tried to highlight overarching concepts and point ahead to their connections with other key notions. The theme of model building is repeated here in the context of different topics.

Also at the end of each chapter, after *The Larger View*, you will find carefully selected *key terms* (**boldface** in the text) that are integrated with *key ideas* (relating to the chapter concepts). This integration often calls out a technical term more than once, sometimes from previous chapters—and that's the idea, for it shows the interrelations of concepts. (Technical terms are introduced only if they are used again in this book; they are not introduced for their own sake and then never used again. The expanded *Glossary* actually contains more astronomical terms than are presented in the text.)

The end-of-chapter material also contains *Review Questions*, which can be answered in a word or two (at most a short sentence) and *Conceptual Exercises*, which require more thought and a longer answer (a few sentences). Finally, many (but not all) of the chapters have a *Conceptual Activity* to provide a hands-on activity relating to one particular concept in the chapter.

Astronomical concepts are highly enjoyable when combined with speculation. Adapting material first prepared by Sheridan A. Simon, a colleague at Guilford College, I have added a section called "The View from . . ." to each part. These are based on astronomy and physics, but with a twist. I hope that you find them fun. You might want to read each twice—before and after each part.

Math and Data

Because this is a conceptual approach rather than a quantitative one, I have deemphasized numbers and equations. Within the text, measured quantities are typically given to no more than two significant figures. In tables, the number of significant figures are greater, generally to the accuracy of the measurement. The "At a Glance" tables provide brief summaries of information at appropriate places in the text. Almost every equation in this book, which are few and carefully selected, is set off as a *Math Concept*. Equations are intended to be a shorthand expression of physical ideas rather than a tool to manipulate numbers or symbols.

The Illustration Program

The art program was carefully reviewed by Dennis Schatz (Pacific Science Museum) and myself to provide a human perspective and scale whenever possible. In astronomy, that is sometimes not possible. We also evaluated the illustrations from the view of a novice student with an aim to simplify and clarify illustrations as much as possible. Color has been used in only those cases in which we thought it would aid the student in understanding the material: for example, in color-coding the interior structure of earthlike planets. The endpaper illustrations provide visual summaries of two key conceptual themes: the origin and evolution of the solar system (front) and the orgin and evolution of a star like the sun (back).

Many of the color photographs are computer-generated in false colors. Because students tend to think that the colors are "real"—those that would be seen by eye—I have tried to be very explicit in the figure legends to identify the false-color images: Appendix G offers additional explanations about this kind of image processing.

Differences from Astronomy: The Evolving Universe

I believe that this clarity, emphasis, and interweaving of essential concepts will reveal the core of astronomical thinking to students. It also marks the main difference between this book and *Astronomy: The Evolving Universe* (6th edition, John Wiley & Sons, 1991), which is a full-featured book for a more in-depth introductory course. The story told in *Conceptual* is one of building up a model of the cosmos (and its parts) from the standpoint of contemporary astronomy. So I have limited the historic development and the people involved with it; for that story, you should turn to *Evolving*. You may also notice that some traditional astronomical topics, such as apparent and absolute magnitudes, are not covered in this shorter book. (Overall, *Conceptual* has about 40 percent fewer words than *Evolving*, and 19 rather than 22 chapters.) I have judged that such topics are not essential to the conceptual development. My students have not missed them!

Supplements

An innovative package of supplemental materials is available to assist in teaching an introductory course with this book. It includes:

- *Instructor's Manual* by J. Wayne Wooten of Pensacola Junior College. This contains detailed chapter outlines and overviews, additional discussion topics, class demonstrations, answers to Review Questions and Conceptual Exercises in the text, and additional resources.
- *Test Bank* also by Professor Wooten. This resource has over 1000 statistically tested multiple-choice questions.
- *Computerized Test Bank.* This computerized classroom management system (for both MS-DOS and Macintosh computers) offers the *Conceptual Astronomy* test bank to develop tests and answer keys.
- *Overhead Transparencies.* These four-color illustrations from the text can be projected in class.
- *Dance of the Planets* (planetarium version). Adopters of *Conceptual Astronomy* will receive a coupon for 15% off the purchase price of this MS-DOS based program. This fascinating software provides a physical simulation of the dynamics of the solar system.
- *Astronomy Video.* Developed in cooperation with the Astronomical Society of the Pacific, this videotape provides short, single-concept segments, mostly as simulations and animations. I selected the segments and wrote the commentary for them.

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Feedback

Any errors in the text are my responsibility. Please write to me if you find any. It is a little-known fact that minor corrections and changes *can* be made in future printings of this edition. I take a special effort to update new printings as they occur. (You can check the bottom of the copyright page to find out which printing you have in hand.) *I remind reviewers to mention this fact when they comment upon any errors; also, please send them to me so I can fix them!* Your feedback can improve this book! Any comments are appreciated; send them to me:

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Note:
Abbreviations are often used for the names of major observatories and agencies (particularly in the figure captions). These are: NASA—National Aeronautics and Space Administration; NOAO—National Optical Astronomy Observatories; KPNO—Kitt Peak National Observatory; CTIO—Cerro Tololo Inter-american Observatory; NSO—National Solar Observatory; NRAO—National Radio Astronomy Observatory; ESA—European Space Agency; ESO—European Southern Observatory; JPL—Jet Propulsion Laboratory of the California Institute of Technology; AATB—Anglo-Australian Telescope Board; NCSA—National Center for Supercomputer Applications.

Fundamental Conceptual Themes

The story line of *Conceptual Astronomy* revolves around the following conceptual themes, which provide the foundation of our understanding of astronomy.

- Scientific models (Section 2.1)
- Heliocentric model of the solar system (Sections 2.3–2.5)
- Kepler's laws of planetary motion (Section 2.5)
- Motion: speed, velocity, and acceleration (Section 3.1)
- Newton's laws of motion (Section 3.2)
- Newton's law of gravitation (Sections 3.4–3.5)
- Energy: its forms and its transport (Sections 4.1 and 10.4)
- Magnetic fields and their interactions with ionized gases (Section 4.5)
- The conservation of energy (Sections 4.6 and 9.2)
- Doppler shift (Sections 5.1 and 9.5)
- Angular momentum and its conservation (Sections 6.5 and 8.4)
- The origin of the solar system (Sections 8.4–8.5)
- Fundamental nature of matter (Sections 9.1 and 18.5)
- Spectra and spectroscopy (Sections 9.1–9.3)
- Atoms and light (Sections 9.3–9.4)
- Ordinary (Section 10.2) and extraordinary gases (Sections 13.5 and 14.1)
- Fusion reactions, nucleosynthesis, and the conversion of matter to energy (Sections 10.5, 13.4, and 14.5)
- The origin of the sun and stars (Sections 12.3–12.4)
- Einstein's theory of general relativity (Sections 10.7, 14.7, and 18.1)
- Inverse–square law for light (Section 11.1)
- The Hertzsprung–Russell diagram (Sections 11.5 and 13.1)
- Hubble's law and the expansion of the universe (Section 16.4)
- Dark matter in the universe (Sections 15.2 and 16.7)
- The origin of the universe in the Big Bang model (Section 18.2)
- The origin of life (Section 19.2)

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P A R

1

Concepts of the Solar System

Unifying Concepts

The earth is one of the planets orbiting the sun. All solar system bodies follow universal laws of motion and gravitation, and so their motions are predictable. The planets and moons of the solar system have diverse physical characteristics, produced by evolutionary processes acting over the billions of years that have elapsed since the formation of the solar system. Our recognition of these processes unifies our view of the solar system.

1 Motions in the Solar System

Central Concept

The motions of astronomical objects you can see by eye follow distinctive patterns and cycles in the sky over both short and long periods of time.

If you watch the sky often for a year, you can observe just by eye the behavior of the stars, planets, sun, and moon. The sun rises and sets; the seasons flow. The moon's illumination changes nightly; different constellations appear as the seasons change. Planets move majestically and sometimes oddly among the stars. Careful study allows you to detect the pattern and timing of these movements and events.

This chapter deals with such observations, naked-eye observations. From these you can sense the regular cycles of motions in the heavens. Long-term observations over months and years can establish the repeating periods of celestial cycles with amazing precision. Most of the brightest naked-eye objects lie in the solar system. Of these, the planets follow the strangest motions of them all.

1.1 The Visible Stars

Before we tackle the motions of the planets, sun, and moon, let's examine the basic backdrop of the sky: the stars.

Constellations and Angular Measurement

If you take the time to study the stars, you'll find that they fall into patterns, designs imposed by your mind (Fig. 1.1). These patterns, such as Orion, are called **constellations**. The official constellations used today (88 in all) are established by international agreement of astronomers. (Appendix I contains seasonal star charts of constellations as seen from the midlatitudes of the Northern Hemisphere.) A special set of the constellations, twelve in all, makes up the **zodiac** (Table 1.1).

If you observe nightly, you'll see that the shapes of the constellations don't change. In fact, if you watched them for your whole life, you wouldn't notice any change. The stars appear to hold fixed positions relative to each other, which we can measure.

How far apart do stars appear in the sky? A sighting and measuring device, such as the extent of your fist held at arm's length, will allow you to measure the angle between one star and another; this angle is the **angular separation** or **angular distance** between two stars. Angular measurement is based on counting by 60: a circle is divided into 360 degrees (°), each degree into 60 minutes of arc (*arcmin* or ′),

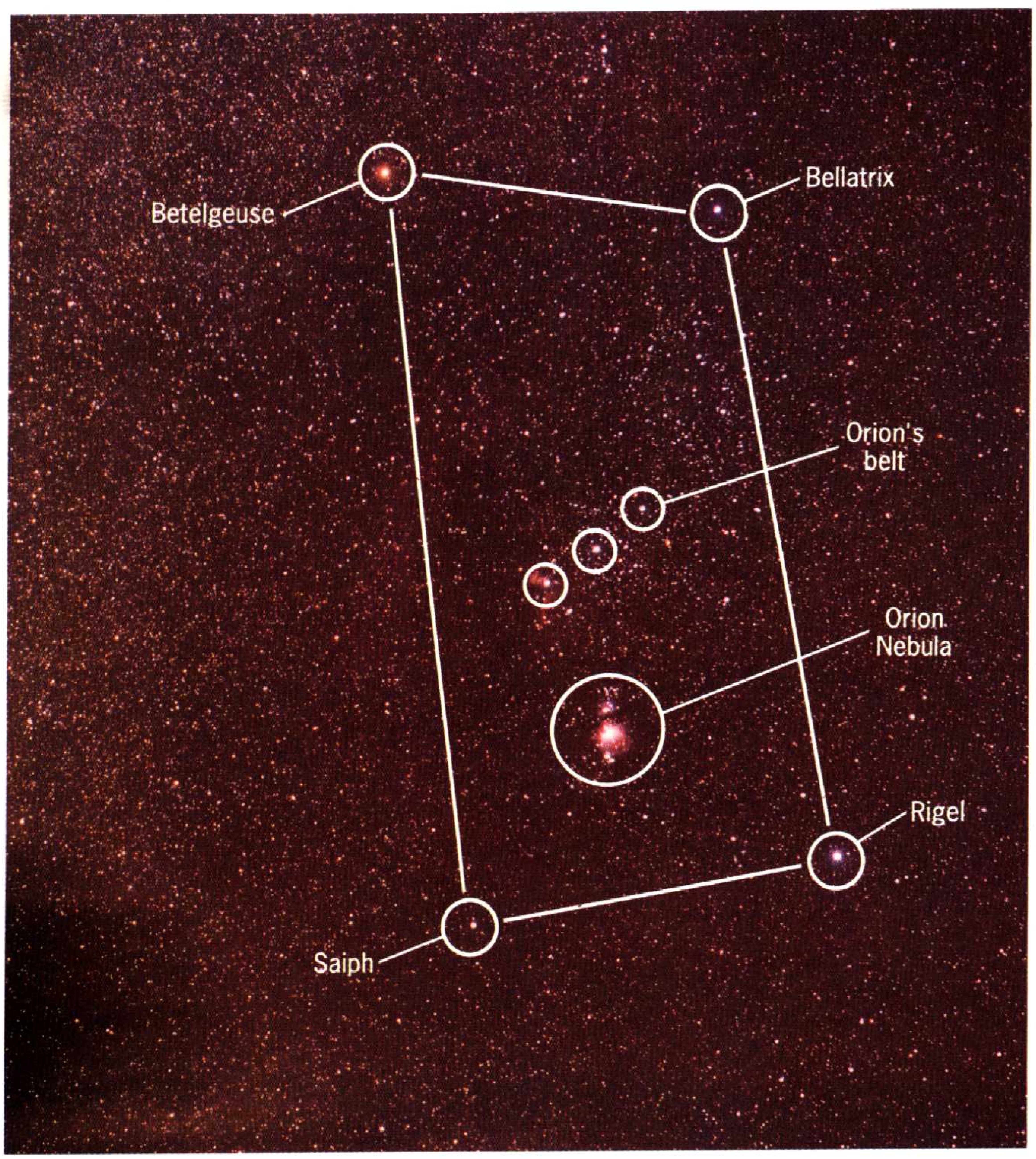

FIGURE 1.1

Time exposure of the stars in the constellation Orion and others nearby. The three bright stars making a diagonal line pointing to the top right form Orion's belt. Below the center star is the fuzzy patch of the Orion Nebula. The very bright star at bottom right is bluish Rigel; to the upper center is reddish Betelgeuse. This photo shows many faint stars that are invisible to the eye. An outline is superimposed of the pattern of Orion, with names of the brightest stars and main features. See the constellation charts for winter in Appendix I to find Orion. (Courtesy Dennis di Cicco, *Sky & Telescope* magazine)