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ABSTRACT

Presented is book five in a series of six books in the University of Illinois Astronomy Program which introduces astronomy to upper elementary and junior high school students. This guidebook discusses the interior of stars, their source of energy, and their evolution. Topics presented include: the physical properties of the sun; model of the solar interior; using known physical laws as guides; the source of solar energy; properties of stars - their luminosities; temperatures; masses; stellar models; the evolution of stars; and birth and death of stars. (Author/DS)

THE UNIVERSITY OF ILLINOIS ASTRONOMY PROGRAM

THE LIFE STORY OF A STAR

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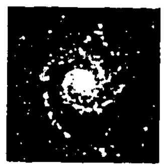

BOOK 5

GUIDEBOOK

1817

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THE UNIVERSITY OF ILLINOIS ASTRONOMY PROGRAM

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PROJECT STAFF

THE UNIVERSITY OF ILLINOIS ASTRONOMY PROGRAM is the product of eight years of research and development by the Elementary-School Science Project, a course-content improvement project supported by the National Science Foundation. The program grew within a logical framework that incorporated writing conferences, classroom trials, evaluation reviews, and rewriting sessions. The staff of professional astronomers and science education specialists was under the direction of J. Myron Atkin, professor of science education, and Stanley P. Wyatt, Jr., professor of astronomy, both of the University of Illinois.

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INTRODUCTION

THE UNIVERSITY OF ILLINOIS ASTRONOMY PROGRAM is a series of six books that introduces astronomy to upper elementary and junior high-school students in a unique way. The program represents a complete restructuring of traditional descriptive school astronomy into a course of study based on selected major concepts that are pursued in depth. These basic themes of astronomy have been picked by professional astronomers to give children fundamental and accurate information about the solar system, the stars, and the galaxies.

Two subsidiary elements are reflected in this program's approach to the teaching of astronomy. First, there is a strong flavor of history throughout the books. Not only are fundamental concepts presented, but students also learn the way in which these concepts were uncovered by astronomers down through the centuries. Secondly, the interdisciplinary nature of astronomy is repeatedly emphasized. Your students will apply principles from several of the physical sciences as they study these books. They will also discover that mathematics is a tool of science.

Major concepts in each book are explored primarily through numerous student activities as well as through the development of models that explain astronomical phenomena. The physical and mathematical underpinnings of each book are developed in the early chapters. Later chapters are then devoted to the application of these principles to a variety of areas in astronomy. Within each book, the development is from simple, basic ideas to an understanding of the concepts and principles which the astronomer has established.

There has been a vast acquisition of new knowledge by astronomers in the past three decades, and the frontiers of astronomy are expanding at an increasing rate. Man is learning more and more about the nature of the universe. THE UNIVERSITY OF ILLINOIS ASTRONOMY PROGRAM is designed to guide your students to a fuller understanding of this universe.

An Outline of the Program

The following book-by-book summary of THE UNIVERSITY OF ILLINOIS ASTRONOMY PROGRAM will give you an overview of the scope of the series.

Book 1, CHARTING THE UNIVERSE, introduces the student to the measurement of sizes and distances of astronomical objects so that a static snapshot model of the universe can be developed. Book 1 includes:

* The measurement of angles and the properties of triangles and scale drawings.
* The use of triangulation to find distances on earth, to the moon, and to the stars.
* Angular diameters as a means of determining the sizes of the sun, the moon, and the planets.
* The inverse-square law of light as a tool for learning distances to stars and galaxies.

Book 2, THE UNIVERSE IN MOTION, is concerned with how celestial bodies move in space and how these motions are observed by astronomers. Book 2 includes:

* A study of the daily motions of the sun, the moon, and stars.
* The motions of the planets.
* Moving models of the solar system.
* Kepler's laws of planetary motion.
* The motions of stars, star-pairs, and galaxies.

Book 3, GRAVITATION, investigates the causes of celestial motion and examines in detail the laws that apply to all moving things in the universe. Book 3 includes:

* The basic concepts of speed, acceleration, force, and mass.
* Gravity at the earth's surface.
* Newton's law of universal gravitation.
* Orbital paths near the earth.
* The motions and masses of planets and stars.

Book 4, THE MESSAGE OF STARLIGHT, turns to the analysis of light as an essential clue to understanding astronomical phenomena. Book 4 includes:

* The behavior of light.
* The wave model and the particle model of light.
* The electromagnetic spectrum.
* The role of spectra in determining stellar temperature, size, and chemical composition.
* The origin of light and the Bohr model of the atom.
* The *Doppler effect* as an aid to understanding the motion of stars and galaxies.

Book 5, THE LIFE STORY OF A STAR, discusses the interior of stars, their source of energy, and their evolution. Book 5 includes:

* The physical properties of the sun.
* Models of the solar interior, using known physical laws as guides.
* The source of solar energy.
* Properties of other stars—their luminosities, temperatures, and masses.
* Stellar models and the evolution of stars.
* The birth and death of stars.

Book 6, GALAXIES AND THE UNIVERSE, takes up galaxies, the largest known units of matter that astronomers have discovered, and investigates the arrangement and motion of them in the universe. Book 6 includes:

* The home galaxy — its contents, its architecture, and the motion of stars within it.
* Other types of galaxies.
* The arrangement of galaxies in the universe.
* Motions of galaxies.
* Cosmology.

Suggestions for Using this Guidebook

You will find this guidebook allows you a great deal of flexibility in presenting the material to your class. You are urged to use it in a way that best suits your particular class, the time alloted for a particular unit, and your own methods of teaching. Since this astronomy material will be new to your students, you will want to study carefully both the student's edition and this guidebook before presenting a unit to your class.

A symbol consisting of a triangle, a circle, and a square identifies each student activity. The activities are performed with simple, readily obtainable materials. But they require careful performance. Try each activity before it is encountered by your pupils. Anticipate the questions and problems your pupils might have as they work through the activities.

Questions raised in the pupil's book that require specific answers are discussed and answered in the guidebook. You will note, however, that many questions are designed to stimulate interest and thought on the part of your students, often as a bridge to the next topic. You will, of course, find no specific answers to these questions.

Each chapter of your guidebook is laid out in a consistent arrangement that will lead you easily through the material in the student's book.

The chapters in this guide are divided in this manner:

* An opening paragraph gives you a concise overview of the chapter.
* The main ideas of the chapter are listed to clarify for you the major concepts. It is not intended that this list be memorized by your pupils.
* A listing of suggested materials includes those items needed for the activities in the pupil's book.
* Suggestions for teaching are arranged to follow the sequence of sections within the chapter. In all cases in this guide, the page references are to pages in your students' book unless it is specified the reference refers to another page in this guide.
* At frequent intervals short sections of background information are introduced to provide additional material for extension of your knowledge.
* Guidelines to help you direct the student activities are identified by the activity symbol as well as by a page reference to the activity in the pupil's book. When required, these sections of the guide provide answers, completed tables, or finished diagrams.
* The book concludes with a guide to the pronunciation of the proper names found in the pupil's book and in the guidebook.

CHAPTER 1

STARS IN YOUR EYES

pages 7-9

In this chapter, the stage is set for the major development of the book. An important distinction is made between merely describing stars and understanding them, in terms of their structure, how they function, and their evolution.

Main Ideas

1. Modern astronomy has been made possible by a knowledge of physics and chemistry and by modern astronomical instruments.

2. There is a big difference between describing the sun and understanding what makes it shine.

3. Each time we discover something new, the discovery may solve old problems, but nearly always it raises a host of new ones.

Suggested Materials

No special materials needed for this chapter.

Suggestions for Teaching

The historical development in this chapter is designed simply as an introduction to a study of the sun. There is no need to spend any length of time discussing ancient astronomers and the contributions of the Greeks.

Because this chapter needs little time for reading and discussion, you probably will want to move immediately into the next chapter.

BACKGROUND INFORMATION *The stars, with the exception of the sun, appear as pin-points of light even through the largest telescopes. Although stars may appear as disks on photographic plates, this image is caused by the photographic process, not by the stars themselves.*

BACKGROUND INFORMATION *Pierre Simon Laplace (1749-1827), French astronomer and mathematician, is noted for his studies on the motion of the moon, Jupiter, Saturn, Jupiter's satellites, and the comets. His popular work,* Exposition on the System of the World, *summarized the history of astronomy up to his time. It included a statement of the "nebular hypothesis," in which Laplace proposed that the solar system was formed from a huge cloud of gas.*

Laplace helped confirm Newton's theories of gravitation. In addition, contributions to the field of mathematics enabled later scientists to make more precise analyses of physical problems.

BACKGROUND INFORMATION *By using cameras attached to telescopes, astronomers have been able to "see" much farther into space than by using telescopes alone. This is because photographic plates may be exposed over long periods of time, thus recording points of light too faint to be detected by the unaided eye. Special processes enable astronomers to photograph in ultraviolet, infrared, and other specific wavelengths of light.*

The spectroscope spreads the light from the sun and other stars into a band of colors called a spectrum. By analyzing the spectrum of a star, astronomers are able to determine many of the properties of the star, such as its temperature, the composition of its outer layers, and its motion along the line of sight.

CHAPTER 2

THE SUN—THE STAR WE KNOW BEST

pages 10-23

Some of the important characteristics of the sun—its distance, size, mass, average density, composition, temperature, and energy output—are discussed in this chapter. Students learn to work with metric units and with powers of ten to express and simplify calculations involving large numbers. Finally, evidence is presented to substantiate the argument for the constancy of the sun's radiation over a long period of time, an important consideration in the development of Chapter 4, "How the Sun Keeps Shining."

Main Ideas

1. Because the sun is so near and can be studied in great detail, it plays a very important part in our understanding of the other stars.

2. Astronomers have been able to learn the distance, size, mass, average density, composition, temperature, and energy output of the sun.

3. The earth receives about two calories of energy each minute per square centimeter when the sunlight strikes its surface at right angles.

4. The sun's luminosity is the total amount of energy it emits in one minute.

5. The sun has been shining at approximately a constant rate for several billion years.

Suggested Materials

cardboard box (approximately 12 in. × 12 in. × 18 in.) white paper
ruler with 1/16-inch divisions ruler with millimeter divisions
tape shoebox dull black paint
centigrade thermometer (with 0.1° scale desirable)

glass baby bottle (with flat sides and rubber nipple)
graduated beaker or cylinder (with cubic centimeter divisions)
cardboard   watch (with sweep second hand)

Suggestions for Teaching

HOW FAR?
page 10

BACKGROUND INFORMATION *Because the earth's orbit is slightly elliptical, the distance to the sun varies during the course of a year. The sun is about 1.5 million miles closer than the average on approximately January 2 and 1.5 million miles farther than the average on about July 4.*

In order to simplify the mathematics as much as possible, many of the relationships and calculations are presented in some length and various tabulations also appear throughout the book.

Significant figures indicate the degree of accuracy attributed to any measured value. The top value shown for the astronomical unit is accurate to within 50 miles, one-half of the unit designated by the *last* significant figure. The second value is accurate to within 5000 miles, the third to within half a million miles, and the bottom value to within five million miles. As a rule, two significant figures are used throughout the book.

HOW BIG?
pages 10-13

Page 10 In this activity, students compute an approximate value for the sun's diameter. The apparatus is, essentially, a pinhole camera. The box need not be exactly the size suggested. With a shorter box the image appears brighter but smaller. With a longer box the image is larger but fainter. The pinhole may be enlarged slightly if the image is too faint to measure.

The box should be positioned so the pinhole points directly at the sun, that is, the back of the box is at right angles to the sun's rays. Measure all distances as accurately as possible, estimating where necessary. A simple method of measuring the image is to mark two opposite points on the image with a very sharp pencil.

Then remove the paper and measure the distance between the pencil marks. Be sure to keep this paper. It is needed again in the activity on page 13.

Pupils need an understanding of similar triangles to do the activity. Point out the diagram at the bottom of page 11. The triangles are similar because the corresponding angles are equal. The apex angles are equal because the sun's rays, traveling in straight lines from opposite sides of the solar disk, cross at the pinhole. The base angles are equal because, by pointing the hole directly at the sun, sides *D* and *d* are parallel.

Since corresponding sides of similar triangles are proportional, side *D* bears the same ratio to side *X* as side *d* bears to side *x*. The diameter of the image, *d*, and the distance from image to pinhole, *x*, have been measured. The distance to the sun, *X*, is known. Therefore, the diameter of the sun, *D*, may be calculated:

$$\frac{D}{X} = \frac{d}{x} \text{ or } D = X\frac{d}{x}$$

As an example of the activity, suppose you measure the distance from pinhole to image as 17⁹⁄₁₆ inches and the diameter of the image as ⁵⁄₃₂ inch. Simplify calculations by converting both measurements into thirty-seconds of an inch; thus, the distance is 562 thirty-seconds. According to the equation shown above, the calculations are:

$$D = 93{,}000{,}000 \frac{d}{x} \text{ miles}$$

$$= 93{,}000{,}000 \times \frac{5}{562} \text{ miles}$$

$$= 827{,}402 \text{ miles}$$

However, since the value for the astronomical unit is accurate to only two significant figures, the result must also be rounded off to two significant figures and becomes 830,000 miles. The actual diameter of the sun to two significant figures is 860,000 miles.

In the shorthand system discussed on page 12, 10^2 is read as "ten squared," 10^3 as "ten cubed," 10^4 as "ten to the fourth power" or, more simply, as "ten to the fourth," etc. Notice that, in this notation, unity becomes "ten to the zero power" or, simply, "ten to the zero."

In this system, each quantity is expressed as the product of two factors: The left-hand factor contains the significant figures; the right-hand factors, the powers of ten. Moreover, it is customary to keep the value of the left-hand factor between 1 and 10.

If the numbers are the result of measurements, there is an important difference between, for example, 8.9×10^3 and 8.90×10^3. While the first expression has only two significant figures, the second expression has three. Thus, the second expression indicates greater accuracy in the measurement.

Page 12 This activity provides practice for students to work with powers of ten.

The answers to the first three problems:

$$2.0 \times 10^{33} = 2{,}000{,}000{,}000{,}000{,}000{,}000{,}000{,}000{,}000{,}000{,}000$$
$$5.7 \times 10^{27} = 5{,}700{,}000{,}000{,}000{,}000{,}000{,}000{,}000{,}000$$
$$1.5 \times 10^{13} = 15{,}000{,}000{,}000{,}000$$

The answers to the next three problems are:

$$40{,}000{,}000{,}000 = 4 \times 10^{10}$$
$$7{,}000{,}000 = 7 \times 10^{6}$$
$$32{,}000{,}000 = 3.2 \times 10^{7}$$

The answers to the final problems are:

$10^5 \times 10^8 = 10^{13}$
Check: $100{,}000 \times 100{,}000{,}000 = 10{,}000{,}000{,}000{,}000 = 10^{13}$

$10^2 \times 10^{14} = 10^{16}$
Check: $100 \times 100{,}000{,}000{,}000{,}000 = 10{,}000{,}000{,}000{,}000{,}000$
$= 10^{16}$

$(4 \times 10^2) \times (3 \times 10^5) = (4 \times 3) \times (10^2 \times 10^5) = 12 \times 10^7$
$= 1.2 \times 10^8$
Check: $400 \times 300{,}000 = 120{,}000{,}000 = 1.2 \times 10^8$

Page 12 The calculations for the problem about light-years are as follows:

$$(5.9 \times 10^{12}) \times 4.3 \text{ miles} = (5.9 \times 4.3) \times 10^{12} \text{ miles}$$
$$= 25.37 \times 10^{12} \text{ miles}$$
$$= 2.537 \times 10^{13} \text{ miles}$$

But since the value used for a light-year is given only to two significant figures, the product must be rounded off to two significant figures also: 2.5×10^{13} miles.

BACKGROUND INFORMATION The name of the closest star that can be seen with the unaided eye is Alpha Centauri. However, it can be seen by viewers in the United States only from the southern portions of Florida and Texas.

Page 13 The answers to the examples in the top activity are as follows:

$$\frac{10^3}{10^2} = 10^1 = 10 \quad \text{Check: } \frac{1000}{100} = 10$$

$$\frac{10^{17}}{10^{11}} = 10^6 \quad \text{Check: } \frac{100{,}000{,}000{,}000{,}000{,}000}{100{,}000{,}000{,}000} = 1{,}000{,}000 = 10^6$$

$$\frac{4 \times 10^3}{2 \times 10^2} = \frac{4}{2} \times \frac{10^3}{10^2} = 2 \times 10 = 20 \quad \text{Check: } \frac{4000}{200} = 20$$

$$\frac{6.0 \times 10^{16}}{2.4 \times 10^3} = \frac{6.0}{2.4} \times \frac{10^{16}}{10^3} = 2.5 \times 10^{13}$$

$$\text{Check: } \frac{60{,}000{,}000{,}000{,}000{,}000}{2400} = 25{,}000{,}000{,}000{,}000$$
$$= 2.5 \times 10^{13}$$

The table on page 13 shows the relationships between units of length in the metric system: 1 kilometer equals 1000 meters; 1 meter equals 100 centimeters; 1 centimeter equals 10 millimeters.

Page 13 Measure the diameter of the image again, using the paper saved from the activity on page 10. Using the same example as before, suppose you measure the distance from pinhole to image as 45.0 cm and the diameter of the image as 4.0 mm. Since both measurements must be expressed in the same units, convert 45.0 cm to 450 mm or 4.5×10^2 mm.

The table shows that 1 km = 10^5 cm. Convert 1.5×10^8 km = $1.5 \times 10^8 \times 10^5$ cm. = 1.5×10^{13} cm. The calculations to determine the sun's diameter are:

$$D = \frac{1.5 \times 10^{13} \times 4.0}{4.5 \times 10^2} \text{ cm}$$

$$= \frac{1.5 \times 4.0}{4.5} \times \frac{10^{13}}{10^2} \text{ cm}$$

$$= 1.3 \times 10^{11} \text{ cm}$$

The actual value for the sun's diameter is 1.4×10^{11} cm.

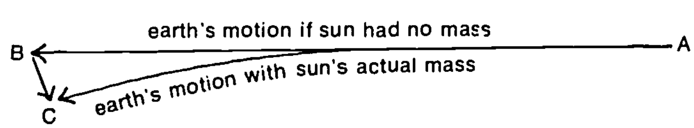
MASS—HOW MUCH?

pages 13-14

The calculations and explanation involved in showing students how astronomers have deduced the sun's mass are quite complex. This brief section merely gives your pupils a few clues as to how the value was obtained. You need not take time to discuss the method at great length. However, for your own information, an expanded development showing how the sun's mass may be deduced by its gravitational effect is included here.

First, the sun's mass relative to the earth's mass is determined as follows:

1. Consider the earth's orbit to be circular with the sun at the center. You know the distance to the sun so you can figure out the circumference of the circle, i.e., the length of the earth's orbit.
2. The earth travels this distance in one year, so you can figure out the earth's speed in its orbit. It turns out to be about 30 km/sec.
3. Consider this diagram.



If the sun had no mass, the earth would travel at a steady speed of 30 km/sec in a straight line, from A to B. But the sun's mass pulls the earth from this path. In one second, the earth curves from A to C. Arrow B-C represents the earth's deviation toward the sun in one second. Astronomers have calculated that the earth is accelerated in the direction of the sun at the rate of 0.60 cm/sec each second.

4. Consider any object, a ball, for example, near the earth's surface. If dropped, it falls at an increasing rate, accelerated toward the earth by the earth's gravity. The ball is accelerated at the rate of 980 cm/sec each second.

5. The earth's acceleration is caused by the mass of the sun. The ball's acceleration is caused by the mass of the earth.

6. Using the law of gravitation, you find that these masses are directly proportional to the accelerations they cause and inversely proportional to the squares of the distances to their centers. Thus:

$$\frac{M_s}{M_e} = \frac{A_s}{A_e} \times \frac{D_s^2}{D_e^2}$$

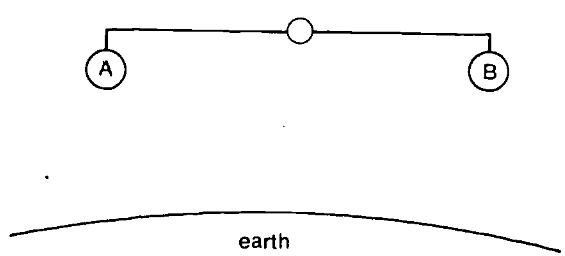
where M_s represents the sun's mass; M_e, the earth's mass; A_s, the earth's acceleration caused by the sun; A_e, the ball's acceleration caused by the earth; D_s the distance from the earth to the center of the sun; and D_e, the distance from the ball to the center of the earth.

$$\frac{M_s}{M_e} = \frac{0.60 \text{ cm/sec each second}}{980 \text{ cm/sec each second}} \times \frac{(1.5 \times 10^8 \text{ km})^2}{(6.3 \times 10^3 \text{ km})^2}$$

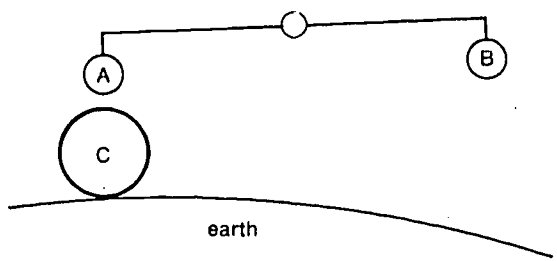
The answer is about 340,000. The actual value for the sun's mass to two significant figures is 330,000 earth masses.

Now, let's calculate the earth's mass by measuring the effect of the earth's gravity on objects in a laboratory.

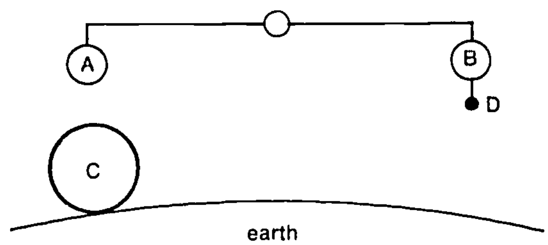
1. From a very sensitive beam balance, support two objects of equal mass as in this diagram.



2. Next, place a very massive object just below one object. The gravitational attraction between these two objects causes the balance to tilt toward the massive object.



3. In order to balance the beam, you add more mass to the other side.



4. The gravitational attraction between *A* and *C* is the same as the attraction between *D* and the mass of the earth. Since you can measure the masses of *A*, *C*, and *D*, you can figure the mass of the earth. It turns out to be about 6.0×10^{27} grams.

Finally, multiply the mass of the earth by the ratio of the masses of the sun to the earth. The mass of the sun is about 2.0×10^{33} grams.

DENSITY—HOW MUCH IN A SHOEBOX?

pages 14-15

The definition used in the text and the values shown at the bottom of page 14 apply to average density. This distinction is stressed again on page 15. Note that the density of water is 1.0 gm/cm^3. The commonly used notation for cubic centimeter is cm^3.

Page 15 The calculation indicates the major steps in determining the sun's volume and results in a value of 1.4×10^{33} cm^3.

Since the sun's mass is 2.0×10^{33} gm, the average density of the sun is:

$$\frac{2.0 \times 10^{33} \text{ gm}}{1.4 \times 10^{33} \text{ cm}^3} = 1.4 \text{ gm/cm}^3$$

ENERGY OUTPUT OF THE SUN

pages 16-20

Page 16 This activity must be performed with care. To simplify calculations, avoid fractional parts of a centimeter in the dimensions of the hole in the cardboard screen. Be sure the screen is large enough to shade the rest of the bottle from sunlight. The entire half of the bottle that will be facing away from the sun should be painted. Fill the bottle completely with water. Arrange the equipment so you can take temperature readings without disturbing the apparatus. Make sure the outside of the bottle is dry. Make all measurements as accurately as you can.

BACKGROUND INFORMATION *Do not confuse the calorie, which represents a unit of heat energy, with the Calorie, the unit popularly used to measure the energy content of foods. It takes 1000 calories to equal one Calorie. The larger unit is usually spelled with a capital letter to distinguish it from the smaller one.*

Refer to the example on page 18. Since the temperature increase is 0.22°C per minute, each cubic centimeter of water in the bottle must have absorbed 0.22 calories of solar energy per minute. So you multiply 0.22 by the total number of cubic centimeters of water to obtain the number of calories received by all the water each minute. The temperature increase per minute times the cubic centimeters of water equals the calories of energy per minute.

Page 18 Divide the result obtained from your calculations by the area of the rectangular hole. This calculation gives the solar constant, or the number of calories received per minute by each square centimeter of the cardboard opening. The unit for this quantity is expressed as calories per square centimeter each minute or cal/cm^2 per minute.

BACKGROUND INFORMATION *The solar constant may be defined more specifically as the amount of solar energy received each minute by a surface of one square centimeter when held at right angles to* *the sun's rays outside the earth's atmosphere at a distance of one astronomical unit from the sun.*

On page 19 the text indicates several reasons why the solar constant is difficult to measure. There are other possible sources of error:

1. Air was in the bottle.
2. The bottle's side was not held at right angles to the sun's rays.
3. Certain atmospheric conditions existed, such as clouds, haze, high humidity, or strong breezes.
4. There was heat loss from the bottle due to cold weather.
5. The sun was low in the sky as it is in the winter or during the early morning or late afternoon.
6. Some heat was absorbed by the glass bottle and the thermometer.
7. Sunlight was reflected from the surface of the glass.
8. The outside of the bottle was wet.

Note that the bottle is painted black to decrease reflected sunlight and that it is placed in a box to reduce heat loss to the surrounding area. Any value between 1.5 and 2.5 cal/cm^2 per minute should be considered excellent. The accepted value for the solar constant is 2.0 cal/cm^2 per minute.

Page 19 With the values given at the bottom of the page, the calculations become:

$$\begin{aligned} A &= 4 \times 3.1 \times 1.5 \times 10^{13} \times 1.5 \times 10^{13} \text{ cm}^2 \\ &= (4 \times 3.1 \times 1.5 \times 1.5) \times 10^{26} \text{ cm}^2 \\ &= 27.9 \times 10^{26} \text{ cm}^2 \\ &= 2.8 \times 10^{27} \text{ cm}^2 \end{aligned}$$

In the equation $L = A \times C$, L is the sun's luminosity; A, the area of the imaginary sphere; and C, the solar constant. The calculation is:

$$\begin{aligned} L &= 2.8 \times 10^{27} \times 2.0 \text{ cal/min} \\ &= 5.6 \times 10^{27} \text{ cal/min} \end{aligned}$$

HOW HOT?

pages 20-22

BACKGROUND INFORMATION In 1879, the Austrian physicist, Josef Stefan (1835-1893), experimentally worked out this important relation-

ship between temperature and radiation, making it possible for astronomers to determine the sun's temperature once the amount of radiation per unit area is known. It also makes it possible to determine the amount of radiation per unit area for a star, once the star's temperature is known.

BACKGROUND INFORMATION *By definition, absolute zero is the temperature at which any object ceases to radiate. Scientists have approached absolute zero to within a very small fraction of a degree in the laboratory.*

In 1848, the English physicist Lord Kelvin introduced the absolute scale. Kelvin knew that when a gas is cooled from 0°C to −1°C, it loses 1/273 of its pressure. He then theorized that if this situation continued, a gas would have no pressure at all at −273°C. He called this temperature absolute zero. Degrees on the absolute or Kelvin scale are the same size as degrees on the Celsius or centigrade scale. Absolute temperatures are indicated by a capital K after the degree symbol and are read as "degrees Kelvin."

Page 21 At the top of the page are most of the calculations in the oven problem. The final result is 5.1 cal/cm² per minute.

Page 21 The purpose of these three calculations is to provide your pupils with values that will enable them to estimate the surface temperature of the sun.

When $T = 1000°K$:

$$E = \frac{8.1 \times 1000 \times 1000 \times 1000 \times 1000}{10^{11}} \text{ cal/cm}^2 \text{ per minute}$$

$$= \frac{8.1 \times 1 \times 1 \times 1 \times 1 \times 10^{12}}{10^{11}} \text{ cal/cm}^2 \text{ per minute}$$

$$= \frac{8.1 \times 10^{12}}{10^{11}} \text{ cal/cm}^2 \text{ per minute}$$

$$= 81 \text{ cal/cm}^2 \text{ per minute.}$$

When $T = 5000°K$:

$$E = \frac{8.1 \times 5000 \times 5000 \times 5000 \times 5000}{10^{11}} \text{ cal/cm}^2 \text{ per minute}$$

$$= \frac{8.1 \times 5 \times 5 \times 5 \times 5 \times 10^{12}}{10^{11}} \text{ cal/cm}^2 \text{ per minute}$$

$$= \frac{8.1 \times 625 \times 10^{12}}{10^{11}} \text{ cal/cm}^2 \text{ per minute}$$

$$= 5.1 \times 10^4 \text{ cal/cm}^2 \text{ per minute.}$$

When $T = 7000°K$:

$$E = \frac{8.1 \times 7000 \times 7000 \times 7000 \times 7000}{10^{11}} \text{ cal/cm}^2 \text{ per minute}$$

$$= \frac{8.1 \times 7 \times 7 \times 7 \times 7 \times 10^{12}}{10^{11}} \text{ cal/cm}^2 \text{ per minute}$$

$$= \frac{8.1 \times 2401 \times 10^{12}}{10^{11}} \text{ cal/cm}^2 \text{ per minute}$$

$$= 1.9 \times 10^5 \text{ cal/cm}^2 \text{ per minute.}$$

Analysis of the preceding computations should establish the sun's temperature somewhere between 5000°K and 7000°K since $9/2 \times 10^4$ cal/cm^2 per minute lies within the range of these two temperatures.

A more accurate estimate is easily accomplished by trial and error. Assign each pupil one temperature value between 5000°K and 7000°K, using values at 100°K intervals. The student assigned 5800°K will find that his calculations produce the desired result. The calculations for 5800°K are:

$$E = \frac{8.1 \times 5800 \times 5800 \times 5800 \times 5800}{10^{11}} \text{ cal/cm}^2 \text{ per minute}$$

$$= \frac{8.1 \times 5.8 \times 5.8 \times 5.8 \times 5.8 \times 10^{12}}{10^{11}} \text{ cal/cm}^2 \text{ per minute}$$

$$= \frac{8.1 \times 1131.6496 \times 10^{12}}{10^{11}} \text{ cal/cm}^2 \text{ per minute}$$

$$= 9.2 \times 10^4 \text{ cal/cm}^2 \text{ per minute.}$$

Note that instead of 1131.6496, we can use 1130 without sacrificing accuracy, simplifying the calculation a good deal.

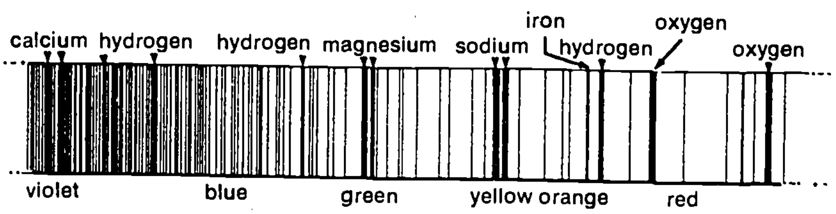
The sun's temperature is about 5800°K. In rough calculations astronomers often use a value of 6000°K. This latter value is used in later chapters of this book.

BUILDING BLOCKS OF THE SUN

page 22

BACKGROUND INFORMATION A spectroscope spreads the light radiated by any object into a series of colors called a spectrum. The colors are spread out according to their wavelengths from violet, with the shortest wavelength, through blue, green, yellow, and orange, to red, with the longest wavelength.

The light emitted by the solar surface produces a continuous spectrum; *there are no missing wavelengths. However, as this light passes through the outer layers or "atmosphere" of the sun, certain wavelengths of light are absorbed. This produces an* absorption spectrum *with dark lines as shown in the diagram.*



Any element in a gaseous state has a characteristic set of wavelengths that it is capable of radiating and absorbing. Scientists have vaporized the elements and photographed their spectra. They have charted the unique patterns of lines—the spectral fingerprints—of atoms under various conditions.

Astronomers compare the dark lines in the solar spectrum with the wavelength patterns of known elements, thereby determining the composition of the sun's outer layers. The lines are called Fraunhofer lines after the scientist who first mapped them.

CONSTANCY OF SOLAR RADIATION

page 23

This characteristic of the sun—the constancy of its radiation over billions of years—will become an important consideration in Chapter 4, "How the Sun Keeps Shining."

CHAPTER 3

WHAT IS THE SUN?

pages 24-38

This chapter develops a model of the sun's interior and discusses how this model was devised from laws governing gravitation, radiation, and the characteristics of gases. Simple analogies will help your pupils visualize some of the abstract laws.

Main Ideas

1. Guided by physical laws, astronomers calculate the conditions that must exist inside the sun. Then they build a mathematical model consistent with the sun's mass, size, luminosity, and chemical composition.

2. The model indicates that the sun is gaseous throughout; that the pressure at every point is proportional to the temperature and density of atoms at that point; and that the temperature, pressure, and density increase continuously from the surface to the center.

3. The rate at which energy is produced inside the sun exactly equals the rate at which it is pouring outward from the sun's surface.

4. Radiant energy travels in very small packets called photons.

Suggested Materials

a heavy book

Suggestions for Teaching

In the opening paragraphs, your students are introduced to the need for a model of the solar interior and the requirements such a model must meet. In order to follow the line of reasoning more easily, the pupils may outline the major points contributing to the building of the model. An outline summarizing these points appears at the end of this chapter on page 30 of this guidebook.

The statement of the law of gravitation in the third paragraph on page 24, although not complete, will be adequate for Book 5.

BACKGROUND INFORMATION *The law of universal gravitation, developed by Isaac Newton, states that every particle in the universe attracts every other particle with a force proportional to their masses and inversely proportional to the square of the distance between them. Mathematically, the law may be stated as:*

$$F \sim \frac{M_1 \times M_2}{d^2},$$

where F *is the gravitational force;* M_1 *is the mass of one particle;* M_2 *is the mass of the other particle;* d *is the distance between the masses; and* $\sim$ *is the symbol of proportionality.*

ENERGY FROM WITHIN

pages 25-26

The first characteristic of the sun to be considered in this chapter is the tremendous amount of energy emitted by the solar surface. This energy must be produced in the interior of the sun and must equal the energy sent out from the sun's surface.

THE STATE OF SOLAR MATTER

pages 26-27

Next, we will study the high surface temperature of the sun. Because heat flows only from hotter to cooler regions, your students should deduce that the sun is gaseous throughout. That must be so, since the surface of the sun is gaseous and since all parts of the solar interior are hotter than the surface.

WHAT IS A GAS?

pages 27-30

In this section, an atomic model of a gas is used to explain the meaning of temperature, pressure, and number density. At this point, the study of gravitational force is temporarily withdrawn.

If pupils express concern over the average speeds of hydrogen atoms as noted on page 28, indicate that in the gas model no atom travels for as long as a second between collisions. In fact, at room temperature, atoms in ordinary air collide about 6×10^9 times a second in an average journey of less than 1/20,000 cm between collisions.

BACKGROUND INFORMATION *When you double the temperature of a gas, you double its pressure. When you double the number density in a gas, you also double its pressure. However, doubling the average speed of the atoms causes the temperature to quadruple. This is because the temperature, sometimes called the kinetic temperature, is proportional to the square of the average speed of the atoms. (The kinetic energy of an atom is expressed:* $K.E. = \frac{1}{2} mv^2$, *where* m *is the mass of the atom and* v *is the atom's speed.)*

BACKGROUND INFORMATION *Number density should not be confused with density. Number density is the number of atoms in a unit volume (usually one cubic centimeter) and is not related to the mass of individual atoms. Density, sometimes called mass density, is the amount of mass in a unit volume. It is the product of the number density and the mass of an individual atom.*

For example, if two cubes of equal volume are filled, one with hydrogen and the other with helium so that there are the same number of atoms in each, the matter in each cube has equal number density. But, since each helium atom has about four times the mass of a hydrogen atom, the matter in the helium-filled cube will have about four times the density as the matter in the hydrogen-filled cube.

Cube A helium-filled

Cube B hydrogen-filled

number density of A = number density of B
density of A = 4 × density of B

GAS AND GRAVITATION

pages 30-33

In this section we will study the problem of the pressure in the interior of the sun. In the previous section we deduced that the temperature increases continuously toward the center of the sun. These temperature changes do not prove that the pressure also increases toward the interior since decreasing number density could cancel out the effects of temperature. To prove that the pressure does, indeed, increase in an inward direction, we will refine the gas model by considering the effect of gravitation.

Develop this section carefully. If your pupils have learned to recognize the forces involved in buoyancy, draw analogies from those experiences.

Page 32 When pupils place their left hand on the top of the book in this activity, they should press down firmly enough to feel an increased pressure on their right hand. An extension of this activity, relating to the analogy of the coins on the next page, would be to add one or more books to the one being supported by the right hand. Students will easily feel the increased pressure on their hands.

BACKGROUND INFORMATION *When astronomers compute the increase in pressure necessary to keep the sun from shrinking, they discover that temperature increase alone cannot account for the pressure. Thus, they deduce that number density also increases continuously from surface to center.*

A PLACE IN THE SUN

pages 33-36

This section describes what the interior of the sun would "look like" in an imaginary trip inside the sun.

BACKGROUND INFORMATION *When an atom emits a photon, the atom loses some of its energy. The photon carries away this energy at the speed of light. When an atom absorbs a photon, the atom gains energy. The energy has been transferred from atom to atom by the process of radiation.*

BACKGROUND INFORMATION *Approximately 10^{45} photons escape from the solar surface each second, or more than 10^{22} photons per second from each square centimeter.*

The sun's internal fogginess, which absorbs most photons, is an important factor in our model, for it prevents the sun from collapsing by keeping its interior hot and maintaining the temperature differences from core to surface.

In describing the density of the solar interior, the text compares the density of lead and water. It may be difficult for students to conceive of the sun's core being ten times as dense as lead and yet being a gas, since in their experiences all gases have been very light. Stress the fact that the sun's core is considered a gas because the matter there *behaves* as a gas. The particles move about freely as in a gas, not bound to each other like particles in a solid.

Following is a list of the main points to remember in a discussion of the sun's interior.

1. We cannot examine the interior of the sun directly.
2. Therefore, we must construct a mathematical model.
3. The model must be consistent with the sun's mass; with its luminosity, size, and composition; and with known physical laws. The same laws, remember, govern earthly and solar matter.
4. The sun's energy is being produced within the sun.
5. Because the sun has been shining at a constant rate for a long time, the energy produced inside must exactly equal the energy being emitted from the surface.
6. In order for energy to flow from inside out, it must be hotter inside than at the surface.
7. The temperature increases continuously from the surface to the core.
8. Since all parts of the interior are hotter than the gaseous surface, the sun must be gaseous throughout.
9. It is known that the pressure of a gas is proportional to both its temperature and its number density.
10. In order for any volume of gas to stay "afloat," the upward push on the bottom must be greater than the downward push on the top, and this pressure difference must exactly balance the force of gravitation on the volume of gas.
11. Therefore, pressure must also increase continuously from the surface to the core.
12. This pressure difference cannot be caused by the temperature increase alone.
13. Therefore, density must also increase continuously from the surface to the core.

14. Atoms emit and absorb photons.

15. In the solar interior, photons travel only short distances before being absorbed.

16. More photons are outbound than inbound.

17. It takes millions of years for energy to travel from core to surface.

18. This delayed radiation keeps the interior of the sun hot, maintaining the temperature and pressure differences from the surface to the center.

19. The temperature, number density, and pressure continuously increase from the surface to the core.

20. The core of the sun is a very dense, very hot gas.

CHAPTER 4

HOW THE SUN KEEPS SHINING

pages 39-50

This chapter investigates the problem that astronomers have faced in trying to explain the source of the sun's radiation for billions of years. The burning-sun and shrinking-sun hypotheses do not explain the sun's long history of constant radiation. The students are introduced to the proton-proton reaction, a process which is used successfully to explain the sun's radiation.

Main Ideas

1. Neither the burning theory nor the shrinking theory can explain the fact that the sun has been shining at its present rate for several billion years.

2. Mass is a special form of energy.

3. The nucleus of a hydrogen atom has one proton; the nucleus of a helium atom has two protons and two neutrons.

4. Hydrogen may be transformed into helium by the proton-proton reaction.

5. In this reaction, a certain amount of mass is changed into radiant energy.

6. Hydrogen fusion reactions take place in the core of the sun, where the temperature is many millions of degrees and the number density is quite high.

7. With the proton-proton reaction as its energy source, scientists estimate that the sun can shine at its present rate for a total of about ten billion years.

Suggested Materials

No special materials needed for this chapter.

Suggestions for Teaching

SCHEMES THAT DID NOT WORK

pages 39-41

BACKGROUND INFORMATION *Hermann Ludwig Fredinand von Helmholtz (1821-1894) was an outstanding scientist famous in many fields. Known as one of the founders of the law of conservation of energy, he also explored the fields of optics, physiology, mechanics, sound, and electricity.*

William Thomson, Lord Kelvin (1824-1907) was the discoverer of the second law of thermodynamics and the inventor of many telegraphic and scientific instrumen . He is most renowned for his work in the field of electricity.

The top illustration on page 40 depicts the interior of the sun, viewed at three different times. The change in shading indicates that the sun becomes denser as it shrinks.

The bottom illustration shows graphically how gravitational force raises the temperature of the sun. The arrows in the left-hand drawing indicate the speed and direction of particles without the influence of gravitational force. It is a random motion due to temperature. The arrows in the middle drawing show the speed and direction of particles under the force of gravitation alone. The arrows in the right-hand drawing show the motion of the particles due to the combined influence of gravitation and temperature. Notice that the speeds in the right-hand diagram are greater than in the left-hand diagram, indicating greater temperature.

Page 41 The calculations for this activity are as follows:

past radius = present radius + (rate of shrinking × number of years)

$$= (7 \times 10^5 \text{ km} + (0.04 \text{ km/yr} \times 5 \times 10^9 \text{ yrs})$$
$$= (7 \times 10^5) \text{ km} + (2 \times 10^8) \text{ km}$$
$$= (700{,}000 + 200{,}000{,}000) \text{ km}$$
$$= 200{,}700{,}000 \text{ km}$$
$$= 2 \times 10^8 \text{ km}$$

Notice that when adding two quantities, you do not add exponents. The second addend is almost 300 times as great as the first.

$$
\begin{aligned}
\text{future radius} &= \text{present radius} - (\text{rate of shrinking} \times \text{number of years}) \\
&= 7 \times 10^{5}\ \text{km} - (0.04\ \text{km/yr} \times 1 \times 10^{8}\ \text{yrs}) \\
&= (7 \times 10^{5})\ \text{km} - (4 \times 10^{6})\ \text{km} \\
&= (700{,}000 - 4{,}000{,}000)\ \text{km} \\
&= -3{,}300{,}000\ \text{km} \\
&= -3 \times 10^{6}\ \text{km}
\end{aligned}
$$

A comparison of the first result, 2×10^8 km, with the astronomical unit, 1.5×10^8 km, indicates that 5 billion years ago the sun would have had a radius larger than the earth's orbit. No life could have existed then.

The second calculation, yielding a negative quantity, indicates that the sun would have completely contracted long before 100 million years from now.

This activity is designed to give pupils an idea as to why the contraction theory cannot work. Actually, the preceding calculations are oversimplified; the rate of contraction is assumed to be constant with time. The real situation is more complicated, with the rate of contraction less in the past and greater in the future.

ENERGY, MASS, AND THE SPEED OF LIGHT

page 41

BACKGROUND INFORMATION Albert Einstein (1879-1955), a German-born physicist, developed the theory of relativity. He also made significant contributions in statistical mechanics and the quantum theory of radiation. Einstein acquired Swiss citizenship and eventually earned his Ph.D. from the University of Zurich. He was elevated to professorships at Zurich, Prague, and Berlin.

Aware that Hitler was on his way to complete power in Germany, Einstein, being Jewish, carefully paved his way for emigration. He resigned his posts at Berlin and eventually joined the Institute for Advanced Study at Princeton, New Jersey, where he remained for the rest of his life.

In this theoretical conversion of matter into energy, the kind of material used makes no difference. A gram of chalk, lead, or hydrogen would yield the same results.

A SCHEME THAT WORKS

pages 41-42

BACKGROUND INFORMATION *Hans Albrecht Bethe (1906-), an American physicist and Nobel laureate, was born and educated in Germany. He came to the United States in 1935 and taught at Cornell University where he was granted a professorship in 1937. During the period 1943-46 he was director of the theoretical physics section at the Los Alamos Laboratory. Bethe is most noted for his theories on atomic properties and on the source of solar and stellar energy.*

MOLECULES, ATOMS, AND NUCLEI

pages 42-44

Pupils should know the difference between an atom and a molecule. See the Background Information below.

BACKGROUND INFORMATION *A molecule is the smallest possible amount of any material or compound. A molecule consists of a definite number of atoms. For example, a molecule of water contains two atoms of hydrogen and one of oxygen, hence, H_2O. A molecule of salt contains one atom of sodium and one of chlorine—$NaC1$. On earth, a molecule of cool hydrogen gas exists as two hydrogen atoms linked together—H_2.*

An atom is the smallest possible amount of any element. Atomic hydrogen is composed of single atoms of hydrogen, for example.

An understanding of this section relies on familiarity with the fundamental relationship between temperature and the speed of particles of a gas: the faster the speed, the higher the temperature.

The description of the atom used in this section and throughout the text is a simplified one, considering only electrons, protons, and neutrons. Other particles, which might be included in a more detailed analysis of the nuclear reactions in the sun, have been purposely omitted.

BACKGROUND INFORMATION *The mass of an electron is only 1/1836 of the mass of a proton or neutron.*

The "electric field bumpers" (page 44) may be compared to "magnetic bumpers" that become evident when the like poles of two small, strong magnets approach each other.

NUCLEI TOGETHER

pages 44-47

BACKGROUND INFORMATION *In atomic fusion, the protons are held together by a little understood, yet tremendously powerful, nuclear force. This attracting nuclear force, though many times stronger than the repelling electrical force, is effective only at very short distances, approximately $1/10^{13}$ cm. At extremely high temperatures, protons have such great speeds that they approach within this critical area in spite of the repelling electrical shields. Hence they are held together or fused by the nuclear force.*

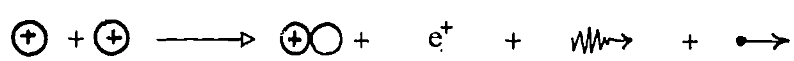
The illustration on page 45 shows protons bouncing apart at relatively "low" and "medium" temperatures, but sticking together at "high" temperatures. The deuterium nucleus contains one proton and one neutron. In the fusion process one of the protons has lost its charge. See Background Information below for a more detailed analysis of this fusion reaction. Different forms of the same element are called isotopes. Deuterium is an isotope of hydrogen. Its symbol is H^2, read as hydrogen two.

Light helium, He^3, has a nucleus containing two protons and one neutron. The nucleus of ordinary helium, He^4, contains two protons and two neutrons.

The proton-proton reaction is purposely simplified in the text. See Background Information below.

BACKGROUND INFORMATION *A more detailed analysis of the proton-proton reaction is as follows:*

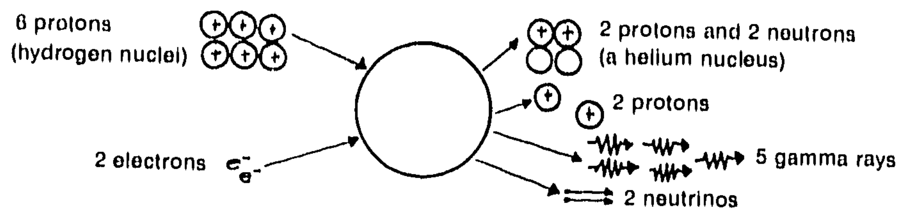
Initially, two protons, each having a positive charge, fuse to form a nucleus of heavy hydrogen, containing one proton and one neutron. One proton has lost its charge. This charge has been carried off by a positron—a particle having the mass of an electron but with a positive charge. Most of the energy released by this fusion process is in the form of a high-energy photon, sometimes called a gamma ray. Also emitted in the process is a neutrino, a tiny particle having no electric charge. Neutrinos are so small and fast-moving that they pass directly out of the



H^1 + H^1 becomes H^2 + positron + gamma ray + neutrino *sun at the speed of light. It has been estimated that a wall of lead, several light-years thick, would be necessary to stop them.*

The positron soon meets an ordinary electron, having a negative charge. In a side reaction, these two particles annihilate each other, yielding another gamma ray. The next steps are the same as those discussed in the text. An alternate summary diagram looks like this:

THE PROTON-PROTON REACTION



Neutrinos carry away only about 5% of the energy released in the proton-proton reaction.

THE PRODUCTIVE PROTON

pages 47-50

Page 47 The total mass of four hydrogen nuclei is 4.032 mass units. The calculation to find the fraction of mass of the four nuclei that turns into radiant energy goes like this:

$$\frac{4.032 - 4.003}{4.032} = \frac{0.029}{4.032} = 0.007$$

Since only 0.007 of the hydrogen mass undergoing the conversion process changes into energy, the remaining 0.993 transforms into helium. With one million grams of hydrogen undergoing the proton-proton reaction, the changes are as follows:

0.993×10^6 gm $= 9.93 \times 10^5$ gm converted to helium
0.007×10^6 gm $= 7000$ gm converted into energy

The number of calories are calculated this way:

$$\begin{aligned} E &= \text{mass} \times 2.1 \times 10^{13} \text{ cal} \\ &= 7.0 \times 10^3 \times 2.1 \times 10^{13} \text{ cal} \\ &= 14.7 \times 10^{16} \text{ cal} \\ &= 1.5 \times 10^{17} \text{ cal} \end{aligned}$$

There are 1,000,000 gm $\times$ 0.993 = 9.93 $\times$ 10^5 grams remaining from one million grams of matter. The final problem in this line of questioning reinforces the idea that the proton-proton reaction consumes a relatively small part of the mass. The calculations are:

$$\frac{5.6 \times 10^{27} \text{ cal/min}}{2.1 \times 10^{13} \text{ cal/gm}} = 2.6 \times 10^{14} \text{ gm/min}$$

$$2.6 \times 10^{14} \text{ gm/min} \times 60 \text{ min/hr} \times 24 \text{ hr/day} = 3.7 \times 10^{17} \text{ gm/day}$$
$$3.7 \times 10^{17} \text{ gm/day} \times 365 \text{ days/yr} = 1.4 \times 10^{20} \text{ gm/yr}$$

BACKGROUND INFORMATION *The number density at the center of the sun is estimated to be about 6 $\times$ 10^{25}/cm^3. But at the interior temperatures of 1.5 $\times$ 10^{7}°K, all atoms are stripped of their electrons. There is still room for the nuclei to move about freely, however, since a proton measures only 1/10^{12} cm as compared to 1/10^{8} cm for a hydrogen atom complete with electron. In spite of the large number density in the sun's core, the matter there is a gas: not a molecular gas as the air in the room, nor an atomic gas, but a gas of nuclei and electrons.*

The problem about the core on pages 48-49 is calculated like this:

$$\begin{aligned} \text{mass of core} &= \text{mass of sun} \times \text{fraction of mass in core} \\ &= 2.0 \times 10^{33} \text{ gm} \times 0.1 \\ &= 2.0 \times 10^{32} \text{ gm} \end{aligned}$$

$$\begin{aligned} \text{mass that can turn into energy} &= \text{mass of core} \times \text{fraction into energy} \\ &= 2.0 \times 10^{32} \text{ gm} \times 0.007 \\ &= 0.014 \times 10^{32} \text{ gm} \\ &= 1.4 \times 10^{30} \text{ gm} \end{aligned}$$

Page 49 The computation is completed as follows:

$$\text{life span} = \frac{\text{mass that can turn into energy}}{\text{mass loss each year}}$$

$$= \frac{1.4 \times 10^{30} \text{ gm}}{1.4 \times 10^{20} \text{ gm/yr}}$$
$$= 10^{10} \text{ yr}$$

The sun's life span is about 10 billion years. Stress the definition used for life span, the total length of time the sun can shine by converting hydrogen into helium.

CHAPTER 5

ON TO OTHER STARS

pages 51-68

This chapter presents the characteristics of stars other than the sun. By plotting stellar luminosities and surface temperatures, the students construct a sample T-L diagram. Interpretation of this diagram and a mass-luminosity diagram teaches them the interrelationships of stellar luminosities, temperatures, sizes, masses, and densities.

Main Ideas

1. Stars vary in luminosity, surface temperature, size, mass, and average density.

2. Stars may be plotted on a T-L diagram, relating temperature and luminosity.

3. Most stars lie on the main sequence, a narrow band on the T-L diagram.

4. Red giants and supergiants lie above and to the right of the main sequence.

5. White dwarfs lie below and to the left of the main sequence.

6. Stars may be plotted on a M-L diagram, relating mass and luminosity.

7. Stellar mass varies with luminosity, except with white dwarfs.

8. The T-L diagram shows that, along the main sequence, the greater the surface temperature a star has, the more luminous, larger, more massive, and less dense it is.

9. Supergiants are the most luminous and massive of all stars.

10. Although red supergiants have low surface temperatures, they are extremely luminous because they are the largest of all stars. Their average densities are very low.

11. White dwarfs are hot stars and are about as massive as the sun, but because they are the smallest of all stars, they have low luminosities and the greatest average densities.

12. Stars on the main sequence produce energy by converting hydrogen into helium.

13. Giants, supergiants, and white dwarfs are very different from main-sequence stars.

Suggested Materials

No special materials needed for this chapter.

Suggestions for Teaching

STELLAR LUMINOSITIES

pages 51-54

Your students will probably be familiar with light meters that are used to determine the setting of a camera. Most light meters contain photoelectric cells, or photocells.

BACKGROUND INFORMATION Photons of light striking the photocell cause a small electric current which can be measured by a sensitive meter. The more photons per second that strike the photocell, the greater the current that is generated. Although the meter measures the electric current, this current is a measurement of the light that strikes the cell.

In addition to visible light, stars emit energy at other wavelengths. Some of this energy may be in the form of ultraviolet, infrared, and even radio wavelengths. In order to take all wavelengths into account, astronomers apply a mathematical correction to the photocell measurement of a star's radiation. In many cases, however, these corrections are slight. For most purposes, photocell measurements are fairly accurate representations of the total energy from a star.

The law may be stated as: "Radiation received from a source varies as the inverse square of the distance from the source," or "Radiation received from a source is inversely proportional to the square of the distance to the source."

There is no need to ask students to check the calculations on page 53. The calculations in the middle of the page compare the luminosity of Sirius with that of the sun. Luminosity is defined on page 20 of the pupil's book as the total amount of energy emitted by a star in one minute.

Rigel is a bright, blue-white star in the winter constellation of Orion. Proxima Centauri, in the constellation of Centaurus, is the nearest star to the sun. It is a companion of Alpha Centauri, but it is invisible to the unaided eye.

STELLAR TEMPERATURES

pages 54-56

The upper illustration on page 55 locates four distinctive stars in the same neighborhood of the sky. Stress the relationship between color and temperature. Reddish Aldebaran in Taurus has a temperature of 3600°K; red Betelgeuse in Orion is 2900°K; bluish Rigel, also in Orion, is 12,000°K; and bluish-white Sirius in Canis Major is 10,000°K.

Other colors of the spectrum—green, yellow, and orange—produce a yellowish-white light when combined in the proper proportions with red and blue. This is indicated in the center illustration at the top of page 56.

THE TEMPERATURE-LUMINOSITY DIAGRAM

pages 56-60

BACKGROUND INFORMATION Ejnar Hertzsprung (1873-1967), a Danish astronomer, was the director of the observatory at Leiden, Netherlands, for many years. His original work, which related the brightness and colors of the stars, was accomplished between 1905 and 1907. Later, in conjunction with H. N. Russell, he refined the data to correlate more closely with stellar-surface temperatures. Hertzsprung also contributed to the field of stellar spectroscopy.

Henry Norris Russell (1877-1957), an American astronomer, was instrumental in the development of astrophysics. His theory on the evolution of stars was favored for many years. He used photography extensively in determining the distances to stars and worked out a method for calculating the dimensions of binary stars that eclipse each other.

Page 57 A duplicate of page 60 is provided on the last page of this guidebook. If you do not wish your students to plot the diagrams in their books, make copies of the duplicate page for each member of the class.

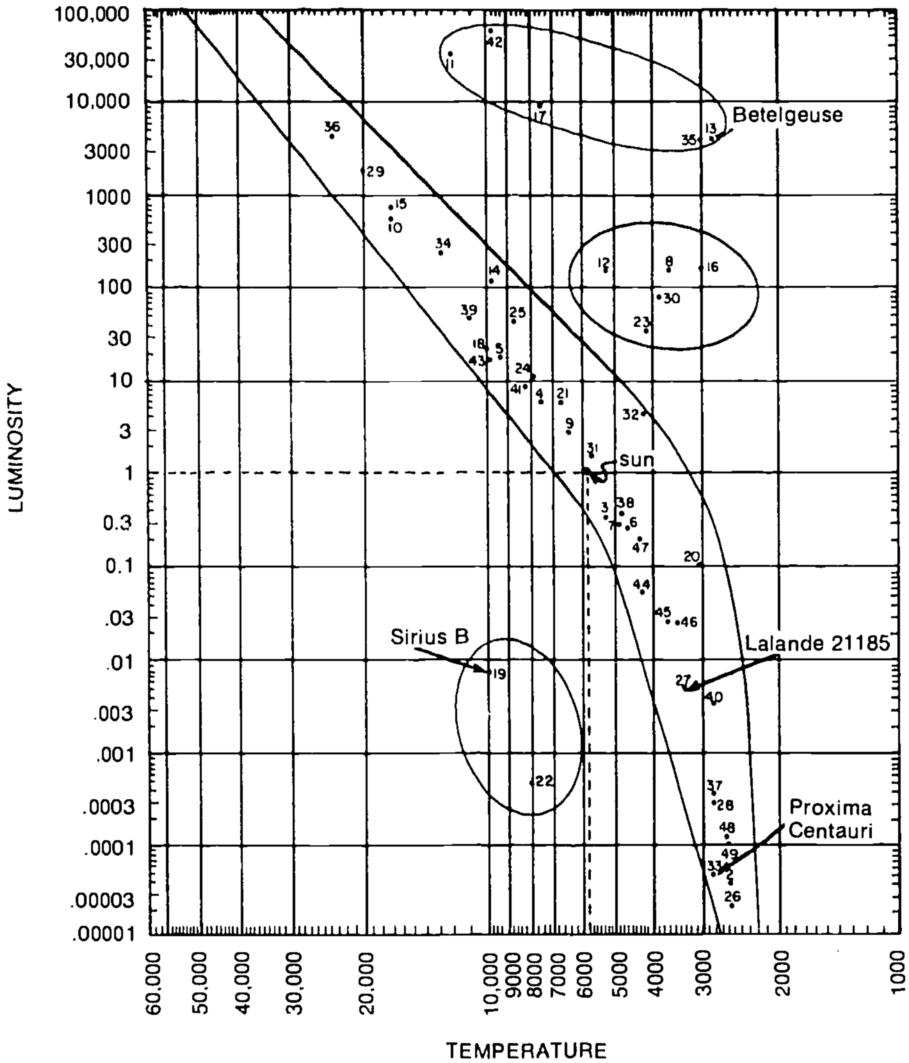
In order to study the special scales of the graph on page 60, pupils should first examine the upper portion of the vertical scale. Start at 1. Notice the intervals between solid lines. Although vertical intervals are the same size on the scale, the range represented by each interval is different. Each interval represents a range ten times as great as the interval below it. For example, the range 10-100 is ten times as great as the range 1-10. Convert the values 1, 10, 100, 1000, 10,000, and 100,000 to powers of 10. They become 10^0, 10^1, 10^2, 10^3, 10^4, and 10^5. Stress the fact that the scale is based on the exponents of ten.

On the scale, exponents that are between the solid lines are fractions and mixed numbers, not whole numbers. Consider 30, for example; 30 is more than 10^1 and less than 10^2. The exponent of ten that corresponds to 30 is somewhere between 1 and 2. Mathematicians are able to calculate that this value is about 1.48. In other words, $10^{1.48}$ is approximately equal to 30. Some of your students will know the exponent is also called the common logarithm of the number 30.

Likewise, the vertical scale continues below unity into fractional parts of one. The horizontal scale is similarly constructed.

Students should plot each star's position carefully, estimating where necessary. When plotting points that lie far from the lines drawn on the graph, it is helpful to line up the proper marks along each margin with a ruler or straight edge of paper. Some students will be more successful if they work with partners.

The T-L plot should resemble the one on the next page. Pupils should examine the plots carefully and see that stars are not scattered haphazardly over the diagram. Cool stars are at the right and stars of intermediate temperatures are in the middle. The most luminous stars are near the top of the diagram; the least luminous are near the bottom. Since most of the low-luminosity stars are relatively cool, you would expect a star selected at random to be cool. However, there are two low-luminosity stars in the diagram that are hotter than the sun.



Your students might label the main-sequence stars in the diagram by defining them with smooth curves as shown in the sample. They should realize, however, that their boundary lines are arbitrary: there are stars outside of the main sequence, to the upper right and lower left.

BACKGROUND INFORMATION *Astronomers customarily call constellations by their Latin names, for example, Cygnus (The Swan). To identify individual stars within a constellation, Greek letters are often used, followed by the possessive form of the constellation's Latin name. The brightest star in a constellation is usually designated by alpha, the next brightest by beta, and so on. Thus, Alpha Cygni is the brightest star in Cyngus.*

Constellations mentioned on the list and their possessive cases are:

LATIN NAME	*POSSESSIVE FORM*	*ENGLISH EQUIVALENT*
Auriga	*Aurigae*	*Charioteer*
Camelopardalis	*Camelopardalis*	*Giraffe*
Canis Major	*Canis Majoris*	*Larger Dog*
Canis Minor	*Canis Minoris*	*Smaller Dog*
Centaurus	*Centauri*	*Centaur*
Cetus	*Ceti*	*Whale*
Eridanus	*Eridani*	*River*
Hydrus	*Hydri*	*Water Snake*
Indus	*Indi*	*Indian*
Leo	*Leonis*	*Lion*
Ophiuchus	*Ophiuchi*	*Serpent Holder*
Orion	*Orionis*	*Orion*
Ursa Major	*Ursae Majoris*	*Larger Bear*

There are exceptions to the brightness rule. For example, the brightest star in Orion bears the name Beta Orionis.

Some stars are better known by names given them by ancient astronomers. For example, Alpha Orionis is better known as Betelgeuse and Beta Orionis as Rigel. Individual star names that appear in the list are shown below with their Greek-Latin designations:

INDIVIDUAL NAME	*GREEK-LATIN NAME*	*CONSTELLATION*
Aldebaran	*Alpha Tauri*	*Taurus*
Altair	*Alpha Aquilae*	*Aquila*
Antares	*Alpha Scorpii*	*Scorpius*
Betelgeuse	*Alpha Orionis*	*Orion*
Canopus	*Alpha Carinae*	*Carina*
Capella	*Alpha Aurigae*	*Auriga*
Deneb	*Alpha Cygni*	*Cygnus*
Fomalhaut	*Alpha Piscis Austrini*	*Piscis Austrinis*
Pollux	*Beta Geminorum*	*Gemini*
Rigel	*Beta Orionis*	*Orion*
Sirius	*Alpha Canis Majoris*	*Canis Major*
Spica	*Alpha Virginis*	*Virgo*
Vega	*Alpha Lyrae*	*Lyra*

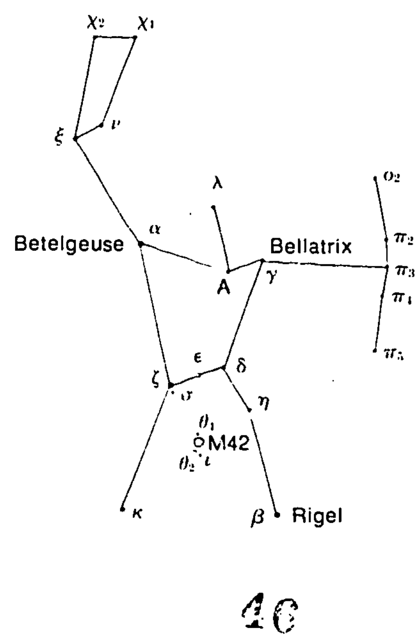
Numerals are also used to name stars, as in the case of 61 Cygni. When it was later discovered that this star was a binary, the individual components were designated as 61 Cygni A and 61 Cygni B.

Many faint stars are known by their catalogue numbers. Examples are Wolf 359, Lalande 21185, Ross 128, and Lacaille 8760. BD + 5° 1668 refers to a certain star in the Bonner Durchmustering, an excellent star catalogue. The designation +5° 1668 indicates the position of the star.

Barnard's Star was named for E. E. Barnard, an American astronomer, who first noticed its fast angular motion across the sky. Luyten 726-8 is the eighth star from the east edge on a photographic plate made by W. J. Luyten of an area in the sky designated by the number 726. Since the star later proved to be a binary, its components were labeled A and B.

The name Omicron-Two Eridani suggests that there are two stars almost on the same line of sight from the earth. These two stars, although appearing to be close together, are actually far apart and are not gravitationally bound to each other. Such stars are referred to as optical doubles. It was later discovered that Omicron-Two Eridani was a true binary, having a white dwarf star, Omicron-Two Eridani B, as its companion.

The faint stars, Pi-One Orionis through Pi-Six Orionis, form the "shield" of Orion. The diagram below shows names and/or letters assigned to some of the stars in Orion. M42 *shows the location of the Orion Nebula.*



STELLAR SIZES

pages 61-63

Proxima Centauri is on the main sequence; Betelgeuse is not. Recall Stefan's law which was introduced on page 20 and was used to calculate the temperature of the sun. General statements made by students should indicate that stars in the upper-right corner of the diagram are very large.

Star No. 27, Lalande 21185, is a main-sequence star with a luminosity comparable to that of Sirius B.

BACKGROUND INFORMATION *Sirius B is a companion to Sirius A, the brightest star in the constellation Canis Major. Sirius B was the first white dwarf star discovered. In 1844, Friedrich Bessel detected its presence because of the gravitational effects it had on its bright sister star. At that time, however, Sirius B was too near Sirius A to be seen. Not until 1862, sixteen years after Bessel's death, was the dwarf star seen through a telescope.*

Stars in the lower-left corner of the diagram have high surface temperatures and low luminosities. Consequently, they must be smaller in size than main-sequence stars.

STELLAR MASSES

page 63

BACKGROUND INFORMATION *No single star exerts enough gravitational force on any other star to change its velocity noticeably. But with a star-pair, small changes in position may be observed from year to year. After many decades these small changes can be plotted to find the track of each star. From a plot of the orbit, you can figure the orbital period of the stars—the length of time needed for one revolution. And by direct observation, you can easily determine the average distance between the two stars.*

Isaac Newton discovered that the combined mass of two orbiting bodies was directly proportional to the cube of the average distance between them and inversely proportional to the square of the orbital period,

$$(M_1 + M_2) \sim \frac{D^3}{P^2}$$

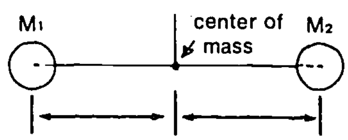
where M_1 *represents the mass of one star,* M_2 *is the mass of the second star,* D *is the average distance between them, and* P *is the orbital period. If we measure the distance in astronomical units (a.u.) and the orbital period in years, we have an equation with the combined masses of the stars stated in terms of the sun's mass,*

$$(M_1 + M_2) = \frac{D^3}{P^2}.$$

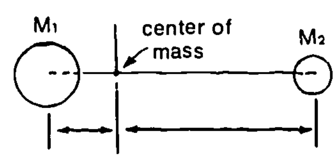
Thus, if two stars move around each other in 10 years and are 5 a.u. apart, their combined mass would be 1.25 solar masses.

$$(M_1 + M_2) = \frac{5^3}{10^2} = \frac{125}{100} = 1.25 \text{ solar masses}$$

Two orbiting stars revolve around a common point known as the center of mass. The center of mass is on a line joining the centers of the two stars and is closer to the larger star. The situation is comparable to the balance point of two balls of clay joined by a thin, rigid piece of wire.



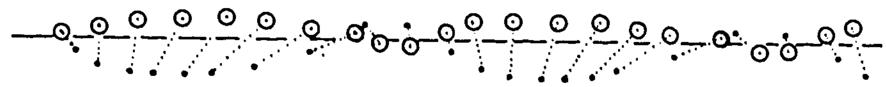
distances equal when M_1 equals M_2



nearer M_1 when M_1 more massive than M_2

If two bodies have equal mass, the center of mass is equidistant from the center of each. The greater the difference in mass, the closer the center of mass of the two bodies lies to the center of the more massive body. For example, the center of mass of the earth-sun system lies within the body of the sun.

By plotting the motion of each star of a star-pair for many years, astronomers can determine where the center of mass lies. The relative distances of the stars from the center of mass lead to the calculation of the individual masses of the stars.



THE MASS-LUMINOSITY DIAGRAM

page 64

BACKGROUND INFORMATION *Sir Arthur Eddington (1882-1944) was director of the observatory at Cambridge, England. In 1916 he began his research on the internal composition of stars which led him to conclude that stars are gaseous throughout and that the mass and luminosity of a star are related. Eddington is also well known for his deep interest and support of Einstein's theory of relativity; he was the first to observe the bending of light rays by the sun during a total eclipse, the phenomenon predicted by Einstein in his theory.*

Since the masses of isolated stars cannot be measured directly, only the sun and stars belonging to star-pairs can be used to develop the M-L diagram. Exponential, or logarithmic, scales are used in this diagram also. The curve shows the relationship between the masses and luminosities of stars in star-pairs.

Using the diagram, you can assume that a star of great luminosity would be very massive. A star with a luminosity one-tenth that of the sun would have a mass about half that of the sun.

When an astronomer uses the M-L relation to find the mass of a single star, he assumes that this relation works not only for stars in star-pairs, but for isolated stars as well.

STELLAR DENSITIES

pages 64-66

The panel near the top of page 66 shows that the constant factor, $\frac{4}{3}\pi$, cancels out in the comparison of the volumes of Betelgeuse and the sun, leaving a ratio of the cubes of the two stars' radii.

A relation, similar to the one used on page 15 to figure out the sun's average density, is used to calculate that of Betelgeuse with respect to the sun:

$$\text{average density (compared to sun)} = \frac{\text{mass (compared to sun)}}{\text{volume (compared to sun)}}$$

$$\begin{aligned} d &= \frac{12}{64{,}000{,}000} \text{ solar density} \\ &= \frac{3}{16{,}000{,}000} \text{ solar density} \\ &= \text{approximately } \frac{1}{5{,}000{,}000} \text{ solar density} \end{aligned}$$

Stress the fact that we are considering here the average density of Betelgeuse, not the density of its core. Also stress that, even though the matter in the core of a white dwarf is very dense, it is not solid but a superdense gas.

The least dense stars are in the upper-right corner of the T-L diagram; the most dense are in the lower left.

Point out the fact that stars at the top of the main sequence also show variation in average density. Stars at the top of the main sequence are less dense than the sun; stars at its bottom are more dense.

SURVEYING IN T-L LAND

pages 66-67

This section summarizes the interrelationships of mass, luminosity, size, and average density that can be interpreted from the M-L and T-L diagrams.

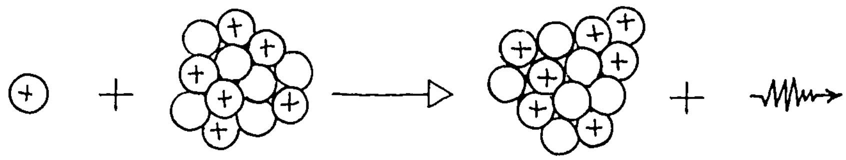
STELLAR MODELS

pages 67-68

A new aspect of main-sequence stars is introduced in this section: that all stars on the main sequence produce energy by converting hydrogen into helium in their cores.

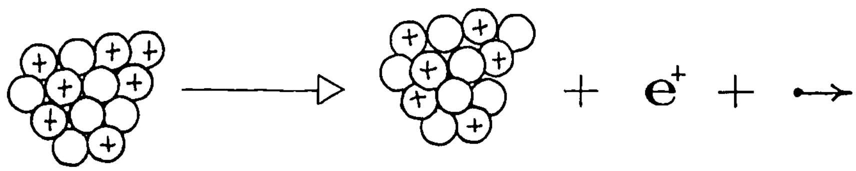
BACKGROUND INFORMATION Energy production in the sun and in the stars below it on the main sequence depends primarily on the *proton-proton reaction. In stars having masses greater than double the sun's mass, the more complex carbon-nitrogen cycle becomes dominant. The sequence of reactions in this cycle is described below strictly for your information and is not intended to be used with pupils.*

1. A hydrogen nucleus, a proton, fuses with the nucleus of ordinary carbon, which is assumed to be found in small amounts in the cores of hot, massive stars. Since a carbon nucleus contains six protons and six neutrons, the reaction produces a structure of seven protons and six neutrons, a light form of nitrogen, N^{13}. In this reaction a high-energy proton, a gamma ray, carries off some energy.



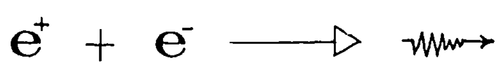
H^1 + C^{12} becomes N^{13} + gamma ray

2. The nucleus of nitrogen is unstable, thus one of the protons loses its electrical charge to become a neutron. This results in a structure having six protons and seven neutrons, a heavy form of carbon called C^{13}. The charge is carried off by a positron, a positively charged electron. Also emitted in this reaction is a neutrino.



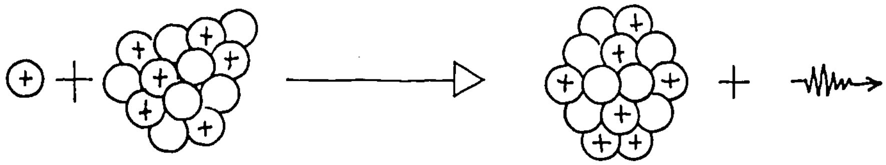
N^{13} becomes C^{13} + positron + neutrino

3. The positron soon meets an ordinary electron. These two particles annihilate each other, yielding a gamma ray.



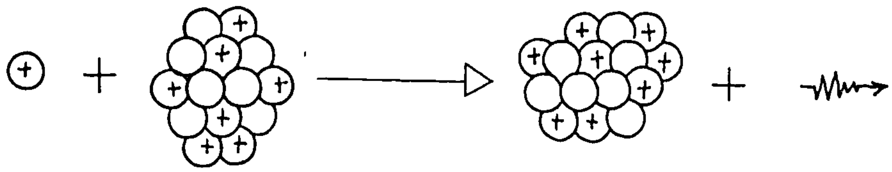
positron + electron becomes gamma ray

4. The C^{13} nucleus produced in Step 2 encounters another proton. These fuse to produce a structure containing seven protons and seven neutrons, the nucleus of ordinary nitrogen, N^{14}. In addition, a gamma ray is emitted.



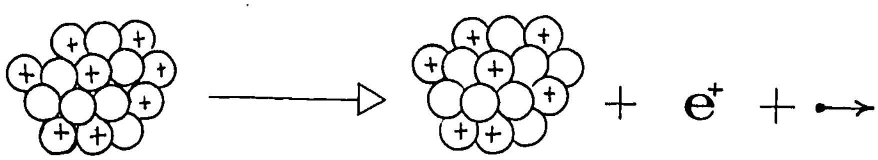
H^1 + C^{13} becomes N^{14} + gamma ray

5. Another proton joins the nitrogen nucleus to produce a form of light oxygen and a gamma ray. The oxygen nucleus contains eight protons and seven neutrons.

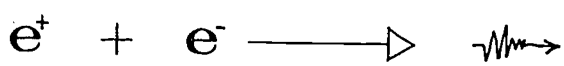


H^1 + N^{14} becomes O^{15} + gamma ray

6. Now one proton in this structure loses its charge to become a neutron. The charge is carried off by a positron which, in a side reaction with an ordinary electron, is destroyed and produces a gamma ray. (See Step 3, above.) This new structure, containing seven protons and eight neutrons, is a nucleus of heavy nitrogen, N^{15}. *A neutrino is also emitted in this reaction.*

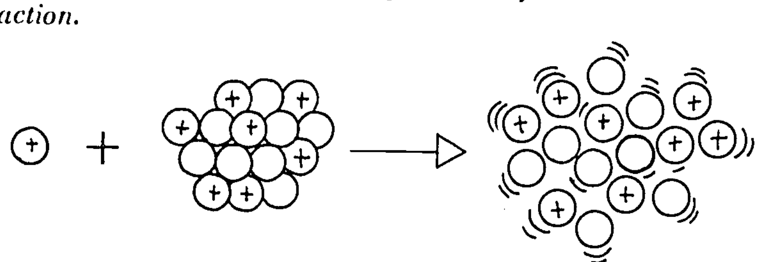


O^{15} becomes N^{15} + positron + neutrino

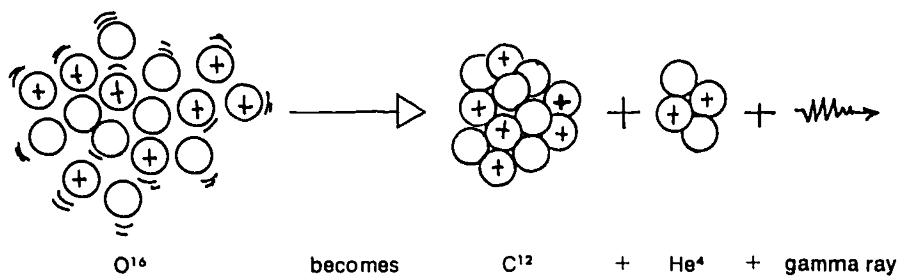


and positron + electron becomes gamma ray

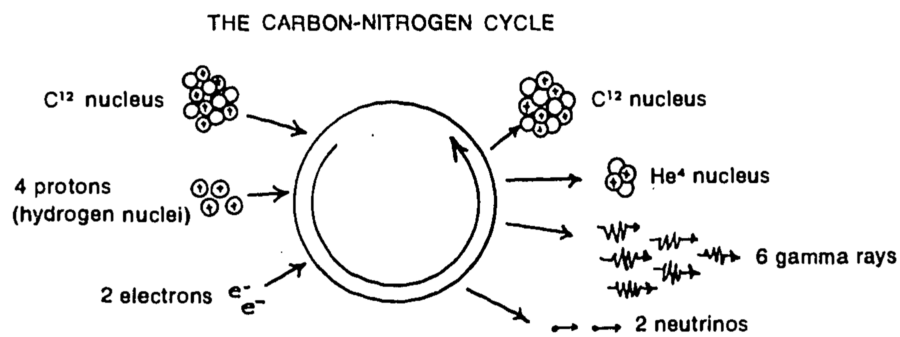
7. Another proton fuses with this nucleus to form a structure containing eight protons and eight neutrons. Although this is the nucleus of common oxygen, O^{16}, *it is a structure in violent agitation. Its component particles are moving about more violently than those in ordinary oxygen. This structure becomes stable by ejecting two protons and two neutrons which combine to form a helium nucleus. The remaining structure contains six protons and six neutrons; it is the nucleus of ordinary carbon. A gamma ray is emitted in this last reaction.*



H^1 + N^{15} becomes O^{16} and



The total result of this series of reactions is as follows:



Note that a carbon-12 nucleus enters the cycle and a carbon-12 nucleus comes out of the cycle. The carbon is used over and over again and is not consumed in the process.

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CHAPTER 6

HOW STARS EVOLVE

pages 69-81

This chapter discusses various stages of stellar evolution. The life spans of some typical main-sequence stars are calculated in order to give direction to the search for signs of aging among stars. By examining T-L diagrams of several star clusters, your students learn that red giants and white dwarfs are stars that were at one time on the main sequence.

Main Ideas

1. The more luminous a main-sequence star is, the shorter is its life span on the main sequence.

2. The stars of a cluster share a common origin and are about the same age.

3. T-L diagrams of many star clusters show that stars with short life spans no longer appear on the main sequence.

4. Clusters with relatively complete main sequences are young; those with much of the main sequence missing are very old. The point on the main sequence where the turnover begins indicates a star cluster's age.

5. Red giants and supergiants have evolved from main-sequence stars.

6. A star begins to leave the main sequence when most of the hydrogen supply in its core is used up.

7. The core then contracts and heats up; the star expands greatly, its surface becoming brighter and cooler.

8. Stars leave the red-giant stage to become white dwarfs.

9. Although its nuclear power plant is shut off, a white dwarf cools off gradually by radiating feebly for billions of years.

Suggested Materials

No special materials needed for this chapter.

Suggestions for Teaching

THE LIFE SPANS OF STARS
pages 69-71

Since the life span of Rigel is only 1/1800 that of the sun, the computation in the upper diagram on page 70 is worked out this way:

$$\begin{aligned}\text{life span of Rigel} &= \frac{1}{1800} \times 10{,}000{,}000{,}000 \text{ years}\\ &= \frac{100 \times 10^8}{18 \times 10^2}\\ &= 5.5 \times 10^6 \text{ or about } 6 \times 10^6 \text{ years.}\end{aligned}$$

Page 70 The calculation at the bottom of the page uses the life span formula to show all but the final steps. These are completed here for you:

$$\begin{aligned}\text{life span} &= \frac{2{,}000{,}000}{52} \times 10^9 \text{ years}\\ &= \frac{200}{52} \times 10^{13}\\ &= 3.8 \times 10^{13} \text{ or about } 4 \times 10^{13} \text{ years.}\end{aligned}$$

Page 71 The calculations are as follows:

$$\text{Zeta Ophiuchi: } \frac{10^{10} \times 10}{4500} = \frac{100 \times 10^9}{45 \times 10^2} = \text{about } 2 \times 10^7 \text{ years}$$

$$\text{Zeta Canis Majoris: } \frac{10^{10} \times 7}{780} = \frac{700 \times 10^8}{78 \times 10^1} = \text{about } 9 \times 10^7 \text{ years}$$

$$\text{Sirius A: } \frac{10^{10} \times 3}{23} = \frac{30 \times 10^9}{23} = \text{about } 1 \times 10^9 \text{ years}$$

$$\text{Procyon A: } \frac{10^{10} \times 2}{5.8} = \frac{200 \times 10^9}{58} = \text{about } 3 \times 10^9 \text{ years}$$

$$\text{70 Ophiuchi A: } \frac{10^{10} \times 0.8}{0.40} = \frac{8 \times 10^{10}}{4} = 2 \times 10^{10} \text{ years}$$

$$\text{61 Cygni A: } \frac{10^{10} \times 0.4}{0.052} = \frac{400 \times 10^{10}}{52} = \text{about } 8 \times 10^{10} \text{ years}$$

$$\text{Wolf 359: } \frac{10^{10} \times 0.01}{0.000021} = \frac{1000 \times 10^{10}}{2} = 5 \times 10^{12} \text{ years.}$$

General statements made by students should indicate that the higher a star appears on the main sequence, the shorter is its life span.

LIFE SPANS VERSUS AGE

page 72

Page 72 At ten years of age, the redwood tree is in its "infancy," the human is young, the dog is in middle age, and the mouse is dead.

HUNTING FOR AGES—THE PLEIADES

pages 72-74

BACKGROUND INFORMATION *The Pleiades cluster in Taurus can best be seen in the evening sky from September to April. It is about 400 light-years from the earth. In our part of the galaxy, nearest-neighbor stars average about 4 light-years apart; in the Pleiades cluster the average is about 1.5 light-years.*

Because all the stars in a cluster are about the same distance from us, their luminosities are easily compared. Thus, the T-L diagram for stars in a cluster is quite accurate.

AN AGE CLUE?

pages 74-75

The T-L diagram of the Pleiades shows that the stars with the shortest life spans, the more luminous stars, are not on the main sequence.

BACKGROUND INFORMATION *The Hyades cluster is in Taurus, the same constellation as the Pleiades. The double cluster of Perseus lies close to the familiar constellation of Cassiopeia; M67 is in the constellation of Cancer, the Crab.*

Names have been given to some clusters, but most are known by catalogue numbers. For example, M67 stands for Messier Object, number 67. In 1781, Charles Messier, the French comet hunter, catalogued about one hundred non-starlike objects in the sky—clusters, galaxies, and nebulae.

TURNING OVER

pages 75-76

A more detailed description of what happens to stars as they leave the main sequence appears later in this chapter.

THE AGING OF CLUSTERS

pages 76-78

Page 77 The diagrams on pages 74 and 75 are drawn to the same scale for the purpose of this activity. The clusters should be arranged with Perseus as the youngest, followed by the Pleiades, the Hyades, and M67.

BACKGROUND INFORMATION NGC 188 stands for New General Catalogue, number 188. This number represents a particular cluster in this catalogue.

OFF THE MAIN SEQUENCE

pages 78-79

It is important to stress at this point that a star's life span is defined as the time it spends on the main sequence. Only at the end of its main-sequence life span does a star's position in the T-L diagram change.

In the illustration on page 79, the shaded areas represent the cores which collapse or shrink. The arrows indicate that the core becomes hotter. Note that the body of the star gets bigger. This lowers the temperature at the surface.

LATER LIFE

pages 79-81

The horizontal branch that is suggested by some of the stars in the T-L diagram might be a return path for stars, showing their positions after they pass through the red-giant stage. Details of this return journey are unknown at present.

CHAPTER 7

A STAR IS BORN

pages 82-93

This chapter describes the formation of stars and how nebulae have been determined to be the only natural birthplace of stars. The two-way exchange of interstellar material is discussed, and your students are presented with the concept that the atoms in their bodies were once part of a star.

Main Ideas

1. Nebulae are huge concentrations of interstellar gas and dust.

2. Within a nebula, an extra-dense eddy may contract under its own gravitational attraction to become a proto-star.

3. As a proto-star contracts further, its temperature and density increase until nuclear reactions occur.

4. At this time, a proto-star becomes a main-sequence star and stops shrinking.

5. The original amount of matter in a star determines where the star positions itself on the main sequence.

6. There is more interstellar matter being used to form new stars than there is being ejected back into space from supernovae, novae, and normal stars.

7. The material that is being ejected into space by exploding stars contains heavier elements than the material that went into the making of the original star.

8. The sun was formed in part from the debris that other stars ejected in their old age.

9. The earth and your body contain atoms that were once part of a star.

Suggested Materials

No special materials needed for this chapter.

Suggestions for Teaching

BETWEEN THE STARS

pages 83-85

BACKGROUND INFORMATION *Although the exact nature of interstellar dust has yet to be learned, it is thought to be made up of solid particles consisting of many atoms clinging together. An interstellar dust particle may be as large as* $1/10^5$ *cm, containing approximately a billion atoms.*

Page 83 The calculations are as follows:
The number of hydrogen atoms in a cubic light-year equals the number of atoms per cubic centimeter times the number of cubic centimeters in a cubic light-year, or

$$\begin{aligned} \text{atoms/lt-yr}^3 &= \text{atoms/cm}^3 \times \text{cm}^3\text{/lt-yr}^3 \\ &= 1 \times (10^{18})^3 \text{ atoms/lt-yr}^3 \\ &= 1 \times 10^{18} \times 10^{18} \times 10^{18} \text{ atoms/lt-yr}^3 \\ &= 10^{54} \text{ atoms/lt-yr}^3 \end{aligned}$$

$$\begin{aligned} \text{mass in a cubic light-year} &= \frac{\text{atoms/lt-yr}}{\text{atoms/gm}} \\ &= \frac{10^{54}}{10^{24}} \text{ gm/lt-yr}^3 \\ &= 10^{30} \text{ gm/lt-yr}^3 \end{aligned}$$

This is not enough matter to form a star: it is only 0.0005 the mass of the sun.

WHERE DO STARS COME FROM?

pages 85-87

Page 85 A recapitulation of the steps in the mathematical activity on pages 85 and 86 follows on the next page.

Step 1: radius $= 10 \times 10^{18}$ cm

$= 10^{19}$ cm

Step 2: volume $= \frac{4}{3} R^3$

$$= \frac{4 \times 3.1 \times (10^{19})^3}{3} \text{ cm}^3$$

$= 4.1 \times 10^{19} \times 10^{19} \times 10^{19}$ cm^3

$= 4.1 \times 10^{57}$ cm^3

Step 3: atoms = atoms/cm^3 × no. of cm^3 (volume)

$= 1000 \times 4.1 \times 10^{57}$ atoms

$= 4.1 \times 10^{60}$ atoms

Step 4: total mass $= \frac{\text{atoms}}{\text{atoms/gm}}$

$$= \frac{4.1 \times 10^{60}}{6 \times 10^{23}} \text{ gm}$$

$$= \frac{41 \times 10^{59}}{6 \times 10^{23}} \text{ gm} = 6.8 \times 10^{36} \text{ gm}$$

Actually, the value of 6×10^{23} given in Step 4 as the number of atoms per gram is more accurate than the value of 10^{24} cited on page 84 of the pupil's text. Now proceed to the last problem on page 86—the number of stars in the nebula.

$$\text{number of stars} = \frac{\text{total mass}}{\text{mass of the sun}}$$

$$= \frac{6.8 \times 10^{36}}{2 \times 10^{33}} \text{ stars}$$

$= 3.4 \times 10^3$ or over 3000 stars with masses similar to the sun's mass.

BACKGROUND INFORMATION The Lagoon Nebula in the constellation Sagittarius shown in the long-exposure photograph on page 87 contains several dark globules.

FROM SPACE TO STARS

pages 87-89

Before a star begins to produce energy by nuclear reactions, it is called a proto-star. Gravitational contraction provides enough energy for a proto-star to become luminous.

FROM STARS TO SPACE

pages 89-90

BACKGROUND INFORMATION *The Crab Nebula, a cloud of gas in the constellation of Taurus, is still expanding at a rate of about 1300 km/sec. After nine centuries it is now approximately 10 light-years wide.*

Supernovae are rare in our galaxy. Only three have been recorded in all of our history: the Crab Nebula by the Chinese in 1054, one in 1572 by Tycho Brahe, and one in 1604 by Johannes Kepler.

During the catastrophic explosion of a supernova, the star becomes very bright, perhaps 10^8 times brighter than the sun. The energy emitted may be more than the equivalent of 10^{26} 100-megaton hydrogen bombs. As much as one-tenth or more of the total mass of the star is expelled. A white dwarf star, the remnant of the explosion, resides in the center of the Crab Nebula.

Explosions of novae are neither so powerful nor so rare as supernovae. About 150 have been discovered in our galaxy. There may have been many more, hidden from view by clouds of dust or too far away to be observed. In a nova explosion, shells of expanding gas may be released into space. Some stars, called recurrent novae, explode periodically. Nova and supernova explosions occur late in the evolution of some stars, somewhere between the red-giant stage and the white-dwarf stage.

The solar wind is a tenuous gas of protons and electrons that streams away from the sun in all directions. It has been estimated that the sun regularly ejects about 10^{33} particles every second. The earth, in its orbit, continually moves through this outbound wind of hydrogen gas.

STARS AND YOU

pages 90-93

It is now thought that the elements heavier than iron were primarily produced in the explosions of supernovae.

The table (page 92) of the first eight elements of the *Periodic Table of the Elements* is intended to suggest to students how it is possible for heavier elements to be built up from hydrogen. In this formation of heavier elements, production of lesser isotopes is often part of the process of fusion before the common isotope of an element is formed. Your students will remember that isotopes of heavy hydrogen and light helium are formed before regular helium can be made from hydrogen. Refer to the discussion of the proton-proton cycle in Chapter 4, "How the Sun Keeps Shining."

CHAPTER 8

TIME, SUN, AND STARS

pages 94-96

This final chapter summarizes the life story of the star we know best, our sun.

Suggestions for Teaching

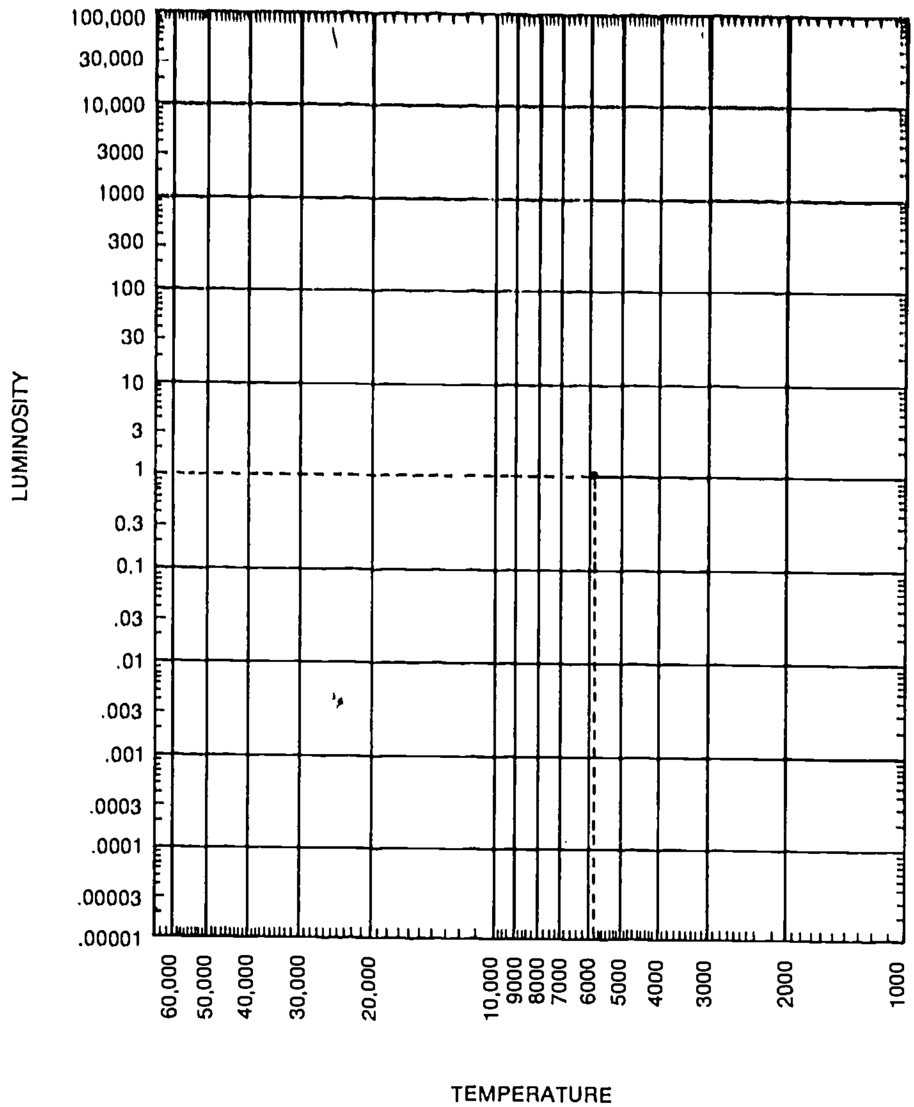
The illustration on page 94 shows the steps in the evolution of the sun up to the present time.

On page 95 the illustration shows steps in the evolution of the sun from the present to the white-dwarf stage. It is believed that, after the sun leaves the red-giant stage, it will become bluer and then cross the main sequence to enter the final stages in its evolution.

PRONUNCIATION GUIDE

Aldebaran	al-DEB-er-un
Alpha Centauri	AL-fa sen-TORE-eye
Altair	al-TAH-ear
Antares	an-TARE-eez
Aquila	AK-weh-luh
Auriga	aw-RYE-guh
Bellatrix	beh-LAY-tricks
Bessel	BESS-ul
Betelgeuse	BET-'l-jooz
Bethe	BAY-tuh
Brahe, Tycho	BRAH, TIE-koe
Camelopardalis	kuh-MEL-eh-PAR-duh-lis
Canis Major	KAY-nis MAY-jer
Canis Majoris	KAY-nis meh-JOR-iss
Canis Minor	KAY-nis MY-ner
Canopus	kuh-NO-puss
Capella	kuh-PELL-uh
Carina	kuh-RYE-nuh
Cassiopeia	KASS-ee-oh-PEA-uh
Centaurus	sen-TORE-us
Cetus	SEE-tuss
Cygni	SIG-nigh
Cygnus	SIG-nuss
Deneb	DEN-ub
Einstein	EYN-stine
Empedocles	em-PED-oh-kleez
Eridani	ih-RID-eh-nigh
Fomalhaut	FO-mul-hoat
Fraunhofer	FROWN-hoe-fer
Gemini	GEM-eh-nigh

Heraclitus	hair-uh-KLIGH-tuss
Hertzsprung, Ejnar	HERTS-prung, EYE-nar
Hyades	HIGH-uh-deez
Hydrus	HIGH-druss
Indus	IN-duss
Lacaille	la-KIGH
Lalande	leh-LAND
Laplace	la-PLAHS
Lyra	LIE-ruh
Lyrae	LIE-ree
Messier	meh-SYEAH
Ophiuchi	oh-fee-YOU-kigh
Ophiuchus	oh-fee-YOU-cuss
Orion	oh-RYE-un
Orionis	or-ee-OH-nis
Perseus	PER-see-us
Piscis Austrinus	PIE-sis aw-STRY-nuss
Pleiades	PLEA-uh-deez
Procyon	PRO-see-on
Proxima Centauri	PROK-seh-muh sen-TORE-eye
Pollux	PAHL-uks
Rigel	RYE-jull
Sagittarius	saj-ih-TARE-ee-us
Scorpius	SCORE-pee-us
Sirius	SEER-ee-us
Spica	SPY-kuh
Stefan	STEF-un
Taurus	TORE-us
Ursa Major	ER-sa MAY-jer
Vega	VEE-guh
Virgo	VURR-go
Von Helmholtz	von-HELM-holts
Zeta Ophiuchi	ZAY-tuh oh-fee-YOU-kigh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TEMPERATURE

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3389