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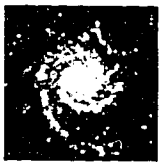
ABSTRACT

Presented is book four 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 document terms the analysis of light as an essential clue to understanding astronomical phenomena. Topics discussed include: thm 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: and the Doppler effect as an aid to understanding the motion of stars and galaxies. (Author/DS)

THE UNIVERSITY OF ILLINOIS ASTRONOMY PROGRAM

# THE MESSAGE OF STARLIGHT

CODIRECTORS: J. MYRON ATKIN STANLEY P. WYATT, JR.



BOOK 4





1817

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New York Evanston London

Cover: THE SPIRAL GALAXY NGC 628 IN PISCES photographed through the 200-inch Hale telescope at Mount Palomar, California.

Richard B. Hoit, Photo Researchers, *Lightning*, page 10.
Mount Wilson and Palomar Observatories, *The Milky Way in Sagittarius*, page 6; *Mrkos Comet, 1957*, page 72.



*Printed in the United States of America*

# PREFACE

We live on a tiny planet revolving around a star that moves through one small corner of the universe. Outward in all directions from our planet lie billions of other stars. Astronomers over the years have accumulated a vast amount of knowledge about these stars, and about the universe as a whole. Most of this knowledge, furthermore, has been gained without the astronomers being able to leave the surface of our planet. It is only in recent years, as you know, that man has made his first attempts to explore space with manned and unmanned spacecraft. You may wonder, then, how scientists have been able to learn so much about the stars while being forced to remain so isolated from them.

In *The Message of Starlight* you will learn that the one thing which tells us more about the stars than anything else is the light that stars give off. And you will learn about the most important tool astronomers use in their study of this starlight—the spectroscope. A *spectroscope* is an instrument that spreads a beam from a light-giving object into a band of colors called a *spectrum*. By studying a star's spectrum, astronomers have been able to gather an amazing amount of information. They have learned a great deal about many stars and particularly about the sun, the star that lies closest to us. You will find out what a spectrum tells us about a star's size, distance, temperature, density, chemical composition, and output of energy. You will also learn that scientists have been able to determine the speed with which stars rotate, to discover stars that shrink and expand, to study the rotation of pairs of stars, and to estimate the speed and direction in which stars as well as entire galaxies are moving. All this and much more have been determined by spectroscopic analysis of the light gathered by astronomers' telescopes. The spectroscope, you will see, is indispensable in interpreting the message of starlight.

*The Message of Starlight* is one of six books in THE UNIVERSITY OF ILLINOIS ASTRONOMY PROGRAM. The program was developed by a group of science educators and astronomers to teach students like you a broad segment of physical science from the point of view of the astronomer. As you learn general principles of science through the astronomer's eyes, you will share his knowledge of the universe that has come from the light of the stars.

## 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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## CONTENTS

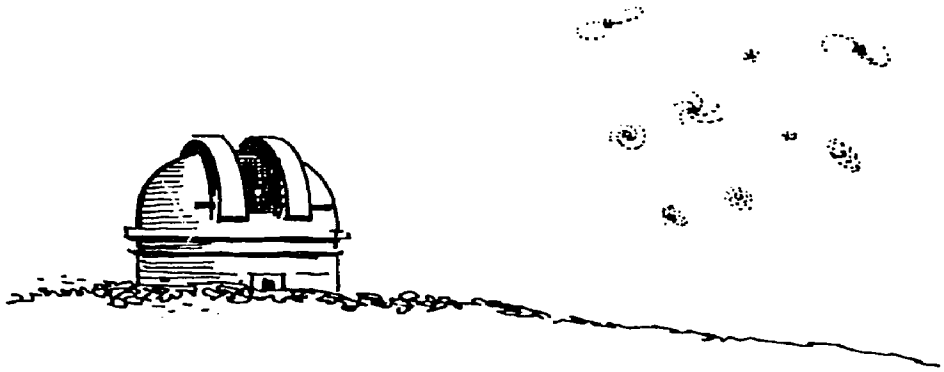
CHAPTER 1

# Starlight

How do we find out what a star is made of?

If you want to find out what a rock is made of, you might drip some acid on it. If the rock fizzes, it may be limestone. Or you might examine the rock under a microscope. Many substances in a rock have definite crystal shapes that help identify what the rock is made of.

What about stars? We can't drip acid on a star and watch for a fizz. We can't put a piece of a star under a microscope to look for crystal structure. Nearly everything we can hope to know about stars and other objects in the sky has to be learned by studying the light they send us.



On a clear dark night, away from the city lights, you can see almost 2500 stars, flickering red, yellow, and bluish-white. With a telescope, you can see millions. Some are so faint that you can hardly tell they are there; others, such as Sirius (SEER-ee-us) and Vega (VEE-guh), shine brightly.

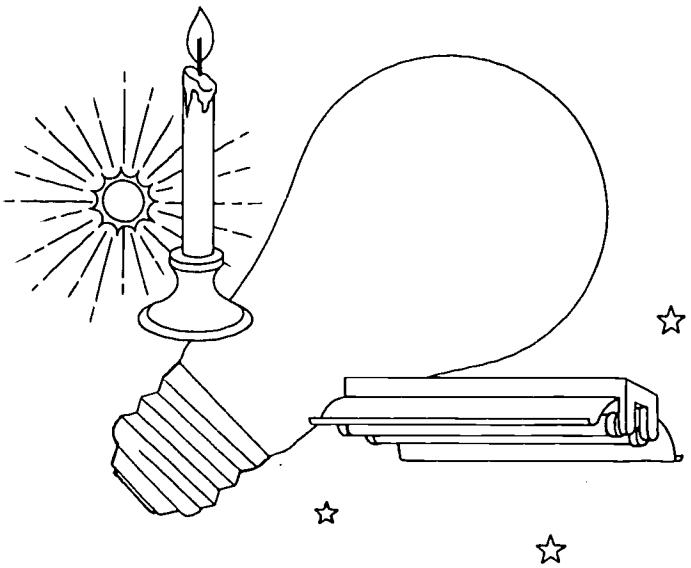
Suppose we lived on Venus instead of on the earth? The dense clouds forever blanketing that planet would block all starlight from its surface and would prevent our seeing any light from the stars. Would we ever know that there are such things as stars? Starlight is our only contact with the stars.

← The Milky Way in the constellation Sagittarius

Except for the sun, all the stars are so far away from us that they appear like pinpoints of light, even in the largest telescope. Imagine that you are in a very dark room where some kind of light has been placed behind a screen. You see the light as a pinpoint reaching you through a tiny hole in the screen. What can you guess about the light source by looking at the light shining through the hole?

What if the light is dull red? What things have you seen that glow dull red? *Coals? A neon sign tube?* If the light is blue, what might the source be? Burning *cooking gas?* A *fluorescent light* tube? Is the light white? White light could be coming from a *light bulb.* Could it even be light from a star, directed through the hole by mirrors? From the pinpoint of light, could you guess anything about the source's temperature? Or how much it weighs?

Astronomers long have pondered over the same kind of puzzle. They have played some poor hunches and some good ones, just as you did with your dark room and screen. Before astronomers could begin to make sense of the stars, they somehow had to decipher the message of starlight. And before they could begin to work out the superpuzzle of starlight, they found that they had to know more about light itself. What causes light? What are the things light can do?



CHAPTER 2

# Behaviors of Light

You can't feel, smell, or hear light, so perhaps you haven't puzzled about it very much. Light has been so much a part of your life from the day you were born that it is natural for you to take it for granted. But what is light? What is it that leaves a star, crosses the vast distance through space, and eventually reaches earth and your eyes?

Over the centuries many scientists have wondered what light could be. At one time people thought of light as something that shot out of the eyes and bounded back to the eyes from every object it struck. Can you think of any objections to this theory?

Even though you have been seeing it all your life, light probably still seems stranger than the objects around you that you can touch. You can observe many things about an object such as a brick or a bird — how much it weighs, what color and size it is, what it is like on the inside. But how many different things can you say about light?

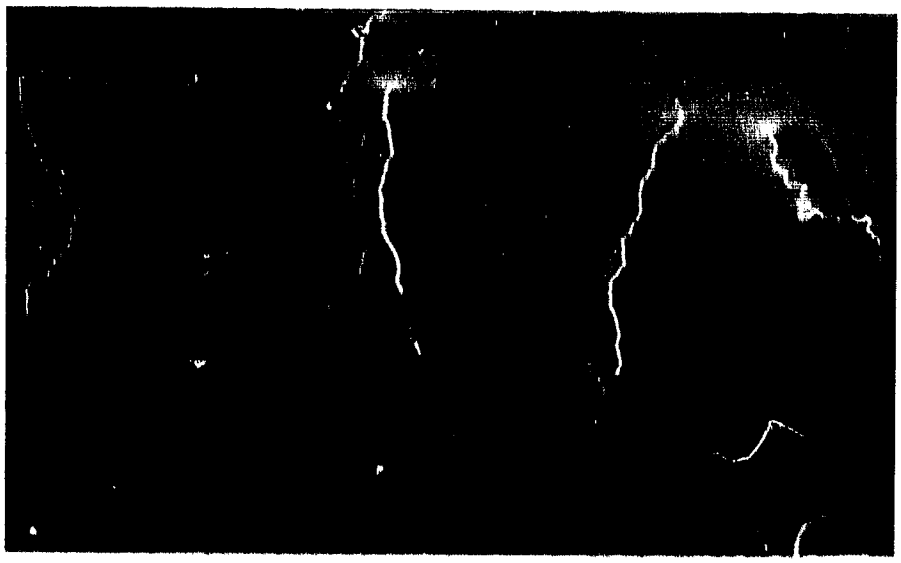
In order to learn about light, you must experiment with it to see what it can do. If you knew all the ways light behaves, you would know all there is to know about light.

## BETWEEN HERE AND THERE

Watch and listen as a thunderstorm approaches. Storm clouds gather. Then a bolt of lightning flashes. Some seconds later you hear the rumble of thunder. Somehow both light and sound got from the storm to you. From your observations, can you compare the speed of light with the speed of sound?

Listen for the sound of a high-flying jet airplane. Do you see the plane where its sound seems to come from? How would things be if light and sound traveled at the same speed?

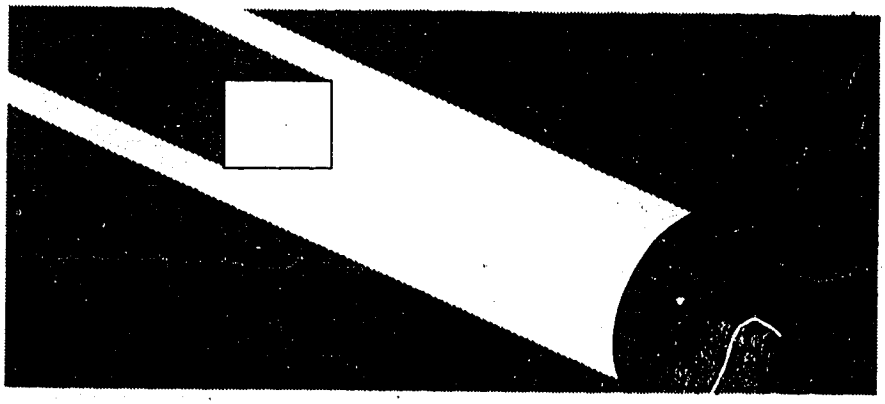
Is it easy to see how fast light travels? Can you get a hint of its speed by flashing a flashlight on and off at a distant mirror and waiting for the reflection to return to you? When you comb your hair before a mirror, do you finish before your image does?



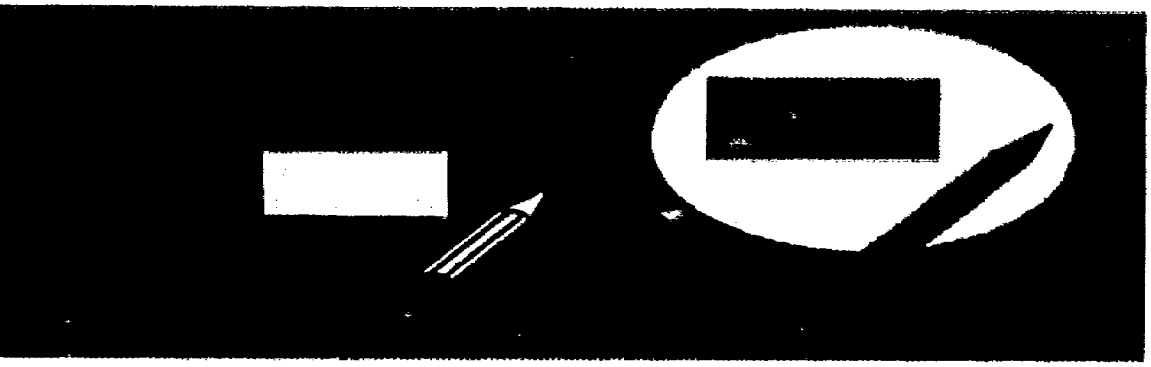
The speed of light is so great that no one really knew whether or not it was instantaneous until about three centuries ago. Today scientists are able to measure the speed of light precisely: light travels at the speed of 186,283 miles per second.

You can examine other behaviors of light by observing objects placed in a strong light beam.

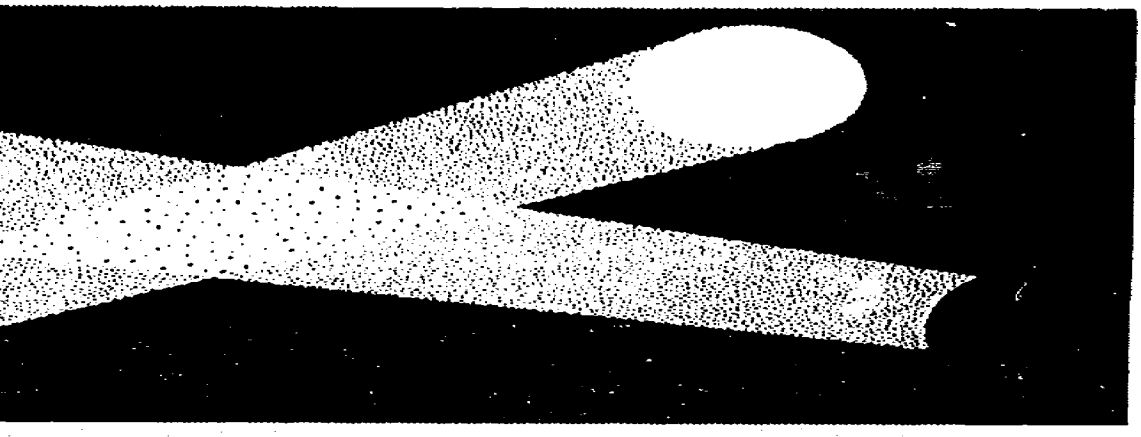
Darken the room and shine a projector beam toward a white screen on the wall. Hold a piece of paper in the beam. The screen and paper are bright, but are they really *sources* of light? Is it possible for the light to brighten the paper without a shadow appearing on the screen? What are shadows?



ps from the paper and screen has been reflected to
ine that the light in the beam has bounced off the
nd a shadow zone stretches out behind. A reflection
always occur together.



ncil into the beam. How can you move your pencil
eam without moving the shadow? Does this tell you
t the path that light takes from the projector to the



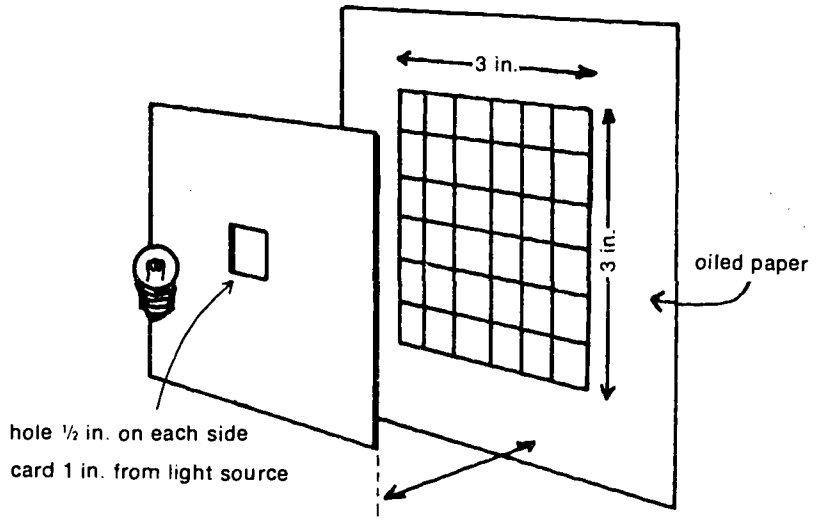
ctors and cross their beams. Put chalk dust in the
oing chalkboard erasers together. Why do the beams
e visible? Are you really seeing the beams? Do the
appear to disturb each other in any way? Does one

beam reflect off the other? Does one beam become fainter after passing through the other?

From one place to another, from a star to a telescope, from a light bulb to a speck of dust—light seems to move in straight lines. It travels fast, much faster than sound. When it strikes objects it seems to bounce and head off in a new direction, and a shadow falls along the old path. But when it encounters another light beam, it passes through as though the other beam weren't there at all.

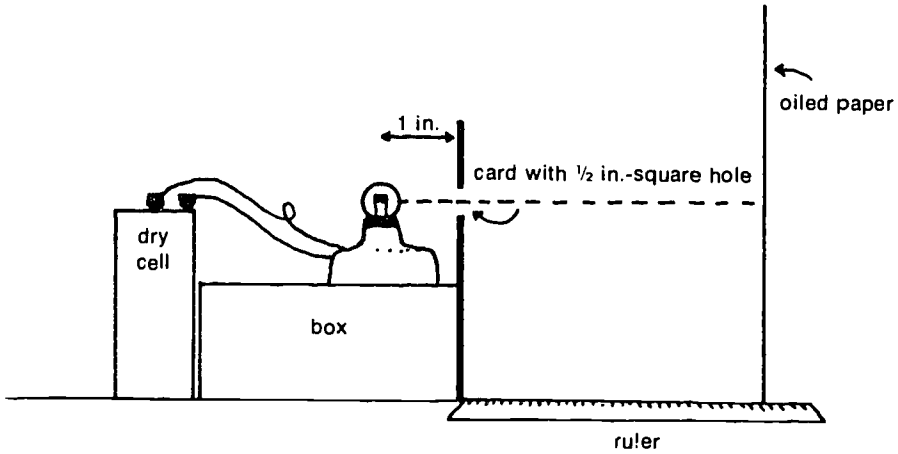
## SPREADING OUT OF LIGHT

The farther away a source of light is, the fainter it appears. The street lights in your neighborhood all have bulbs of the same size, but you know that the lights down the street look fainter than the ones nearby. How much fainter does a light become as you look at it from a greater and greater distance?




To help answer this question, cut a half-inch square from the center of a piece of cardboard. Place this square hole one inch from the filament of a flashlight bulb. Draw a three-inch square in the middle of a piece of paper. Divide this large square into half-inch squares. Rub the paper with salad oil so that light can be seen through the paper. Hold it at different distances from the light.

How many squares receive light when the paper is held one inch from the bulb? Two inches? Three? Four? What does this experiment tell you about the amount of light each square receives when the screen is at different distances from the light?




Careful measurements will show you that when the paper is placed one inch from the bulb, up against the hole in the cardboard, light covers one of the squares. But when you move the paper two inches from the bulb, the same amount of light spreads out and covers four squares. A square's share is now only one-fourth of what it was. At three inches, a square receives one-ninth of the light it receives at one inch. At four inches, a square receives only one-sixteenth of the spread-out light. The amount of light that falls on a square any distance away can always be found by dividing the light at one inch by the square of the distance to the source. Light behaves according to this *inverse-square law.*

The inverse-square law tells how much light will fall on an area at any distance from a point source, compared with the amount that falls on the area when it is a unit distance away. The street light two blocks away sends to your eye $1/2^2$, or one-fourth, as much light as the street light one block away. Only $1/5^2$, or one twenty-fifth, as much reaches you from the street light five blocks away.

## GATHERING LIGHT

On some clear, moonless night when you are far away from city lights, look at the landscape to see if it is lighted by the stars. It will be almost as dark as the bottom of a mine shaft at midnight. When you look into

the sky, however, your eyes gather enough light to see two or three thousand of the brightest stars. Without the aid of a telescope, your eyes cannot gather enough light to show you the other billions of stars that are there. In nearly any small patch of sky that appears black to you, there are actually millions of stars. If astronomers are to study these faint stars, they somehow must collect the feeble light that reaches us from the dark distances of space. Let's explore some of the ways they gather light. When astronomers want a record of starlight, they often capture it on film.

In a darkened classroom, or at the end of a long, dark hallway, make a few "stars." A string of miniature Christmas tree lights makes a good constellation. You can catch homemade "starlight" on a piece of white cardboard. Face away from the lights and hold the paper up. Only a small amount of the light will fall on the paper.

No matter which way you hold the paper, and no matter how close to the bulbs, you cannot make the bulbs appear as pinpoints of light on the paper. To do so, you must do something to the light.

Try gathering the light with a concave mirror. Face the mirror toward the bulbs and move it around until the image falls on the paper. You'll probably get splotches of light instead of sharp

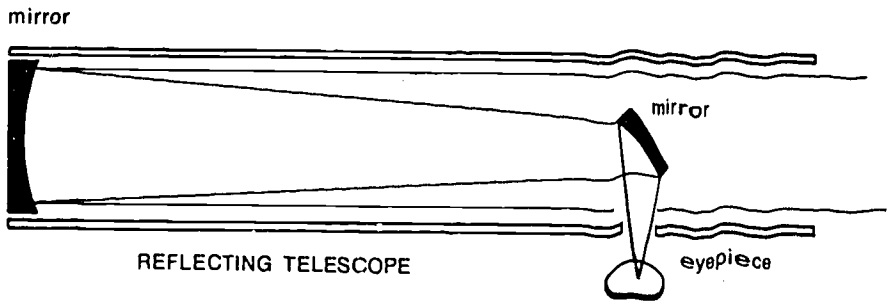
images. Are the images of the "stars" black and white? Or are they the same colors as the lights? What do you notice about the size of the images?

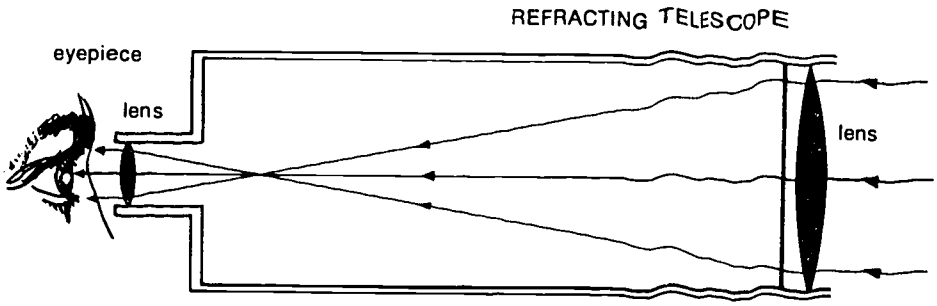
Because the mirror is curved, the reflected light will form images of the "stars." The mirror is much larger than your eye. It captures more light from the "stars" than your eye does.

The bigger the mirror, the more light it will capture and the brighter the image it will reflect. A telescope that uses a concave mirror to gather and focus starlight is called a *reflector*. The surface of the mirror is polished to a very smooth finish so that the images it forms will be sharp. Reflectors often have a second mirror to focus the image outside the telescope, where astronomers can place instruments to record the starlight.

There is another way to gather light and form images. Try it with a magnifying lens. Use the lens the way you would a burning glass. Move the lens closer or farther away until the "constellation" is brought into focus on the paper. The "constellation" may seem small, but it should show up as bright specks of light that you can see clearly. What difference would it make if you used a larger lens?

A telescope that uses lenses to gather and focus starlight is called a *refractor*.

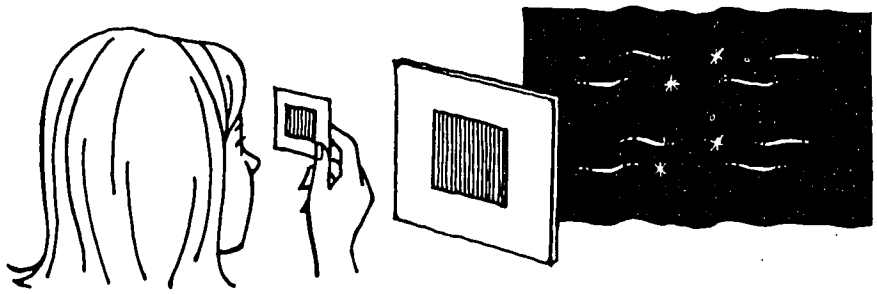



## COLORS IN LIGHT

What more can astronomers do with light than to gather it and focus it with mirrors and lenses? Is there more to light than what you see when you look at a lighted bulb?

Darken the room as much as possible, stand about ten feet from your cluster of stars, and look at them through a diffraction grating. Look for the rainbow of colors for each light.



The band of colors on either side of a light is the *spectrum* of the light given off by the bulb. Hold the grating in various positions until you have the spectrum spreading out from side to side.

Before astronomers could hope to find out what the stars are made of, they had to learn some of the ways light behaves, as you have. In the 1600's Isaac Newton was one of the first to study spectra. He used a glass prism instead of a grating, but like you, he worked in a darkened room. We often have to work in the dark to study light.

## ON YOUR OWN

Look at the sky on a clear night. Pick out a region between three bright stars and try to estimate the number of stars you can see in this area with your unaided eyes. Now scan the same region with a pair of binoculars. How many more stars are visible?

Peer into a mirror with one eye. Hold a ruler close to your face to measure the diameter of the pupil of your eye. The pupil is the circular hole through which light enters the eye. Now measure the diameter of one lens of your binoculars. Divide the diameter of the lens by your pupil's diameter. Square this number to find how much more light a binocular lens gathers than does your eye.

The Hale Telescope at Mount Palomar has a mirror 200 inches in diameter. How many times larger than your pupil is this mirror's diameter? Again, square this number to find out how much more light the 200-inch telescope gathers than does the unaided eye.

CHAPTER 3

# Ways to Think About Light

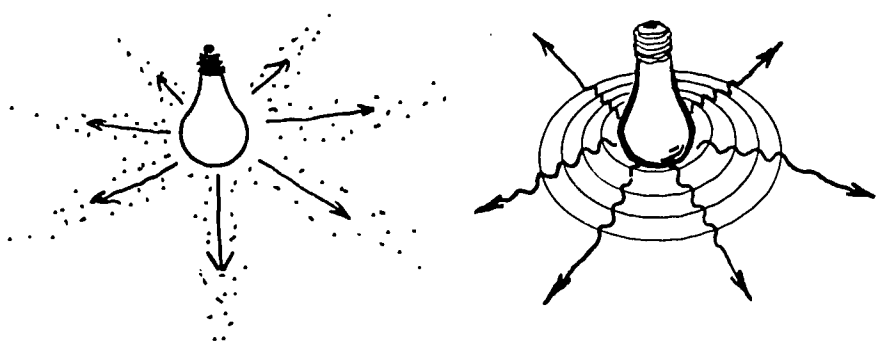
In some ways the behavior of light resembles the behavior of familiar objects.

Light travels away from its source. So do the pellets of buckshot from a shotgun. So do waves on a pond after a pebble has been dropped into the water.

Light is reflected from objects. So is a ball as it bounces off a barn, and so is a water wave as it strikes a smooth wall.

Two beams of light cross without disturbing one another. So do two streams of fast-moving pellets if the pellets are small enough and are not too close together. Do water waves coming from different directions cross without disturbing one another?

Suppose you think of light as a stream of buckshot. You don't have to believe that light really is buckshot. But to form mental pictures of light, it is helpful to use a buckshot model. This model of light is called the *particle model.*



Scientists have found it useful to think about light from the sun or a light bulb as streams of particles even smaller than atoms, moving out in all directions from the source. The more particles striking your eye per second, the brighter the light appears. The farther away from the light you are, the fewer are the particles that reach your eyes, and so the dimmer the light appears.

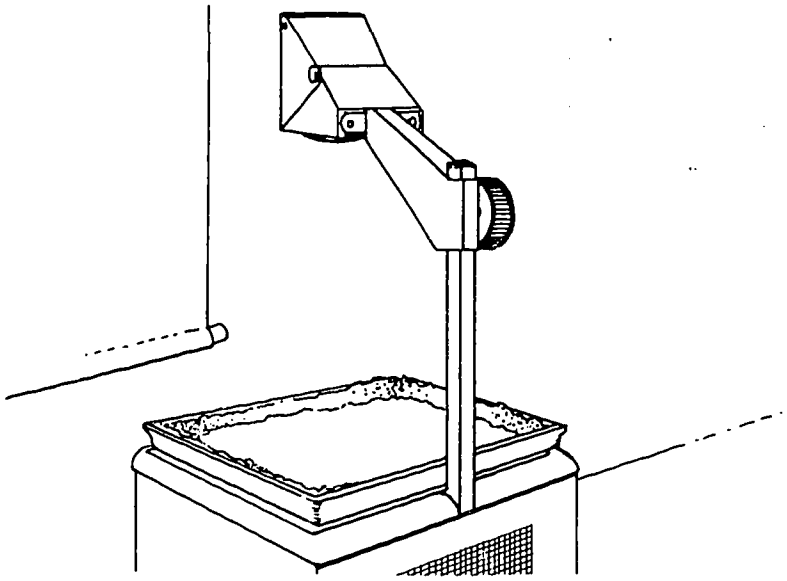
Scientists sometimes find it helpful to think of a *wave model* of light as well as a particle model. Waves behave in some of the same ways that light does. Light from the sun or a bulb can be thought of as waves moving outward in all directions from the source. Like waves on water, the closer to the source, the larger and stronger are the waves that reach you; the light appears brighter. Farther from the source, the waves are spread out and smaller; the light appears dimmer. You see the light only as long as the waves strike your eyes.

Again, you don't have to believe that light really is a wave of something traveling through space. But the familiar behavior of waves on a pond may be a useful picture to keep in mind when you think about the characteristics of light.

The wave model and the particle model of light are based on familiar objects. But don't mistake models for the real thing. Models serve as convenient ways of helping you visualize something you can't otherwise imagine easily.

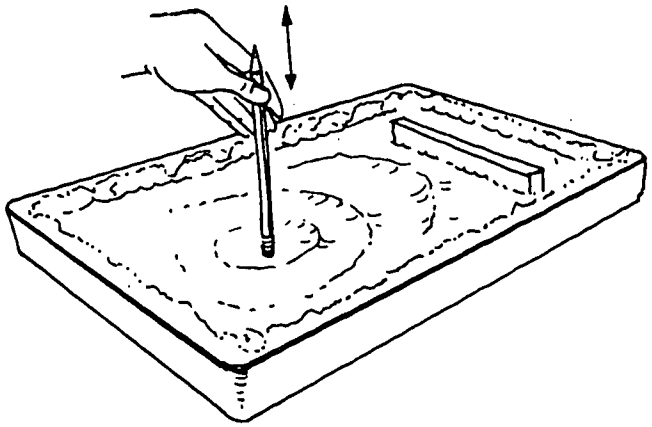
## WAVES ON WATER

Use a large, flat plastic tray, to make a ripple tank. Place the tray on an overhead projector. Pour in water until it is one-fourth inch deep. Dip your finger into the water to make waves. Focus the projector on the ripples until they produce dark shadows on the screen.

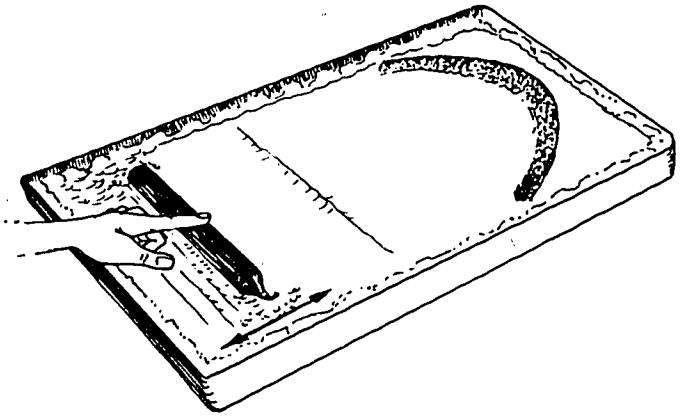


Now make some *point source* wave. Dip the eraser end of a pencil into the water at regular intervals. Using a regular dip-and-lift motion, practice making waves until you can produce a smooth series of ripples moving outward. Study the way the waves move by watching the screen. Notice that waves reflect. They bounce off the sides of the tray.

Place wads of cotton around the edges of the tray to keep the waves from reflecting too much. Place a barrier of paraffin in the ripple tray. Notice what happens to waves that strike it. Does the barrier cast a shadow?



Make waves at opposite ends of the tray at the same time with two pencils. Do waves pass through each other?



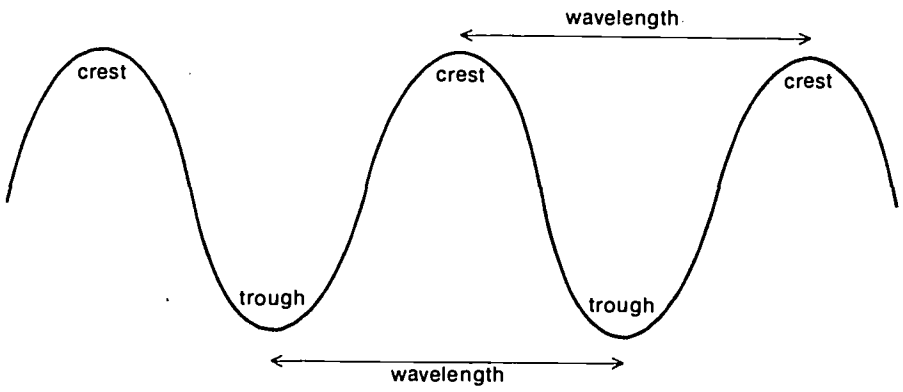
Make some straight waves by gently rolling a candle back and forth at one end of the ripple tray. Pulse the waves with a steady beat and watch them cross the screen.

Now mold a clay barrier in the curving shape of a parabola you see in the illustration at the bottom of page 20.

Place the curved barrier at one end of the tray. Make a single straight wave at the other end and carefully observe the reflected wave. A bright spot shows where the reflected waves all cross at the focus of the barrier.

## MORE WAVES

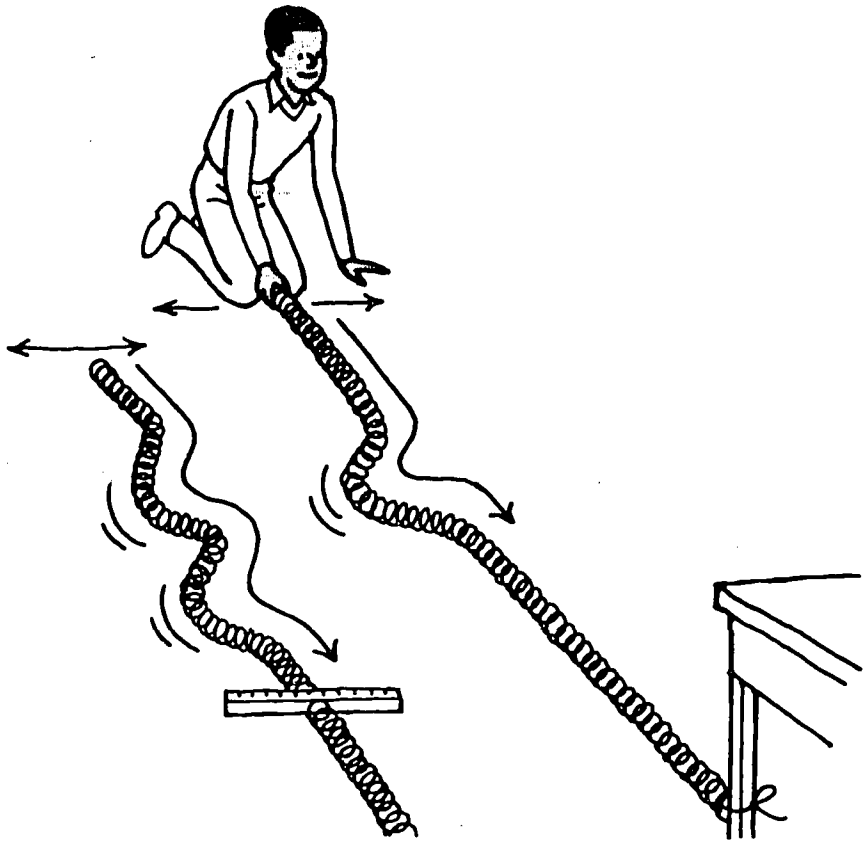
An excellent way to watch waves is with a Slinky. Fasten one end of the coil to the bottom of a table leg and stretch the Slinky along the floor. Move the other end from side to side across the floor with a regular rhythm. Watch the waves as they travel along the coil.




Each wave you make has a *crest* and a *trough*. The distance from the top of one crest to the top of the next crest is called the *wavelength* of the wave. Is the separation between troughs the same as between crests? Move your hand at different speeds to make waves that have different wavelengths. Make a single wave and watch what happens when it hits the table leg. Does a wave on a Slinky behave like a water wave?

Make a barrier with a ruler halfway down the coil. Press the ruler firmly to the floor while someone makes a wave. Is there a reflection? Is there a shadow?

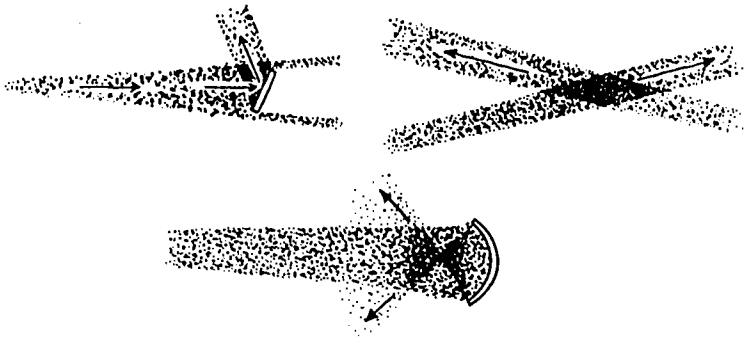
Next, have someone else hold one end of the coil while you hold the other end. On signal, each person makes a single wave. Do the waves stop each other? Now one person makes two waves in quick succession while the other makes only one. Do they pass through each other?



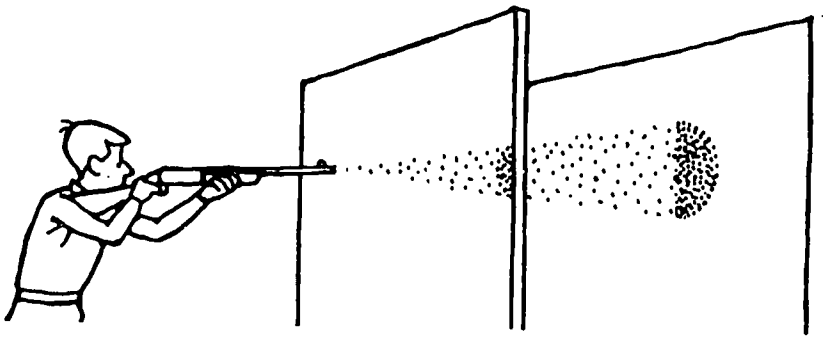
The wave model helps us visualize how light gets from one place to another. Waves can be reflected, leaving shadows behind. Waves can pass through one another, and they can be focused.

The particle model can do all these things, too. Particles can be propelled from here to there. They can be reflected to form shadow zones. If we make particles small enough, streams of them pass through each other. A concave mirror can reflect a stream of particles to a focus.

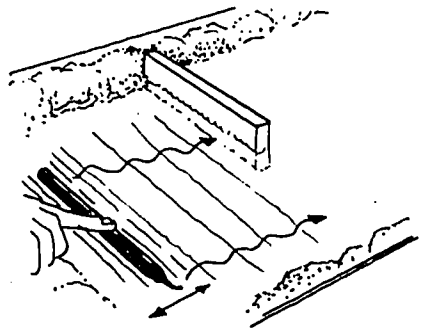
Do you need both models of light? Or can you get along with just one?



Put both models to a further test. Find a situation in which a stream of particles will act in one way and waves in another. Then we can see how light behaves in the same situation.



Think about light going past the edge of a wall. Visualize first the particle model and then the wave model. If you imagine light as a stream of buckshot passing the wall, what sort of shadow would you expect?

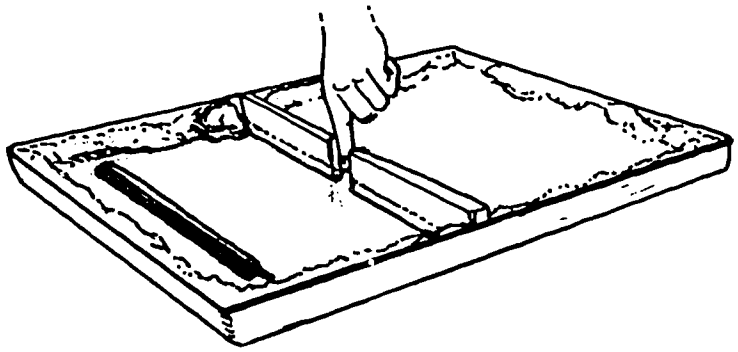


Look more closely at what happens to a wave passing the edge of a barrier. Place a paraffin block halfway across the ripple tray, as you see in the drawing above.

With a candle, produce straight waves at one end of the tray just as you did before. Observe what happens to the waves as they pass the edge of the block.

Here is a case where the particle model and the wave model predict different events. In one model there should be a sharp shadow without any bending at the barrier. In the other model you will observe some bending around the edge, called *diffraction.*

In your ripple tray, set up a barrier of paraffin blocks with a narrow opening, as shown in the illustration below. The opening should be about one-half inch wide. The paraffin blocks should fit snugly against the edges of the tank. Place cotton wads around the rim of the tray to prevent reflection.

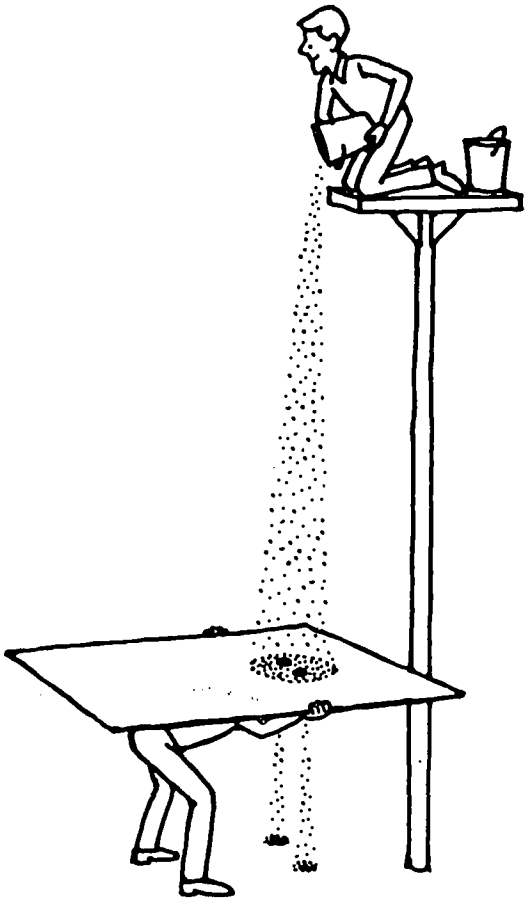


Now make regular straight waves with the candle and watch them when they pass the opening in the barrier. Does it appear as though new waves are being made with an imaginary pencil located at the slot? What shape are these waves? Can you explain why? Try to make a drawing of what happens.

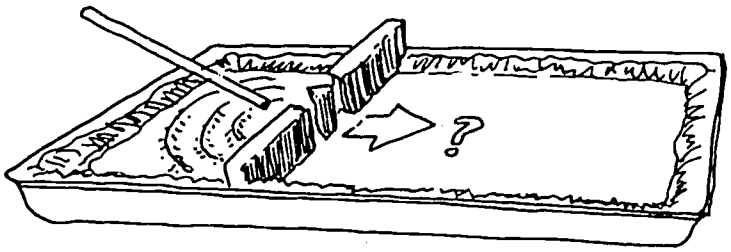
Imagine that someone climbs to the top of a flagpole and pours several buckets of buckshot pellets toward you in a steady downpour. You are safe beneath a shield in which there is a single hole. Nearly all the pellets bounce off the shield, but a few of them fall through the hole. Would you expect the stream to spread out after going through the hole, the way waves do?

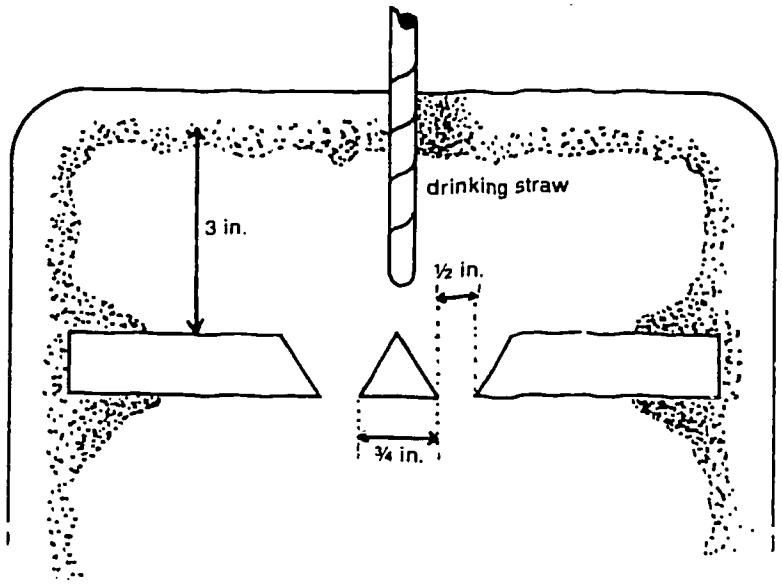
Suppose there are two holes in the shield. As the picture on page 25 shows, the two streams of pellets coming through the two holes do not interfere with each other. What would you see on the ground? What if the pellets streaming through the holes were particles of light?

In your ripple tray, make a paraffin barrier that has two openings instead of one. The openings should have the shapes and dimensions shown in the illustration on page 26. It is difficult to make regular waves with a candle. Far better waves can be made by

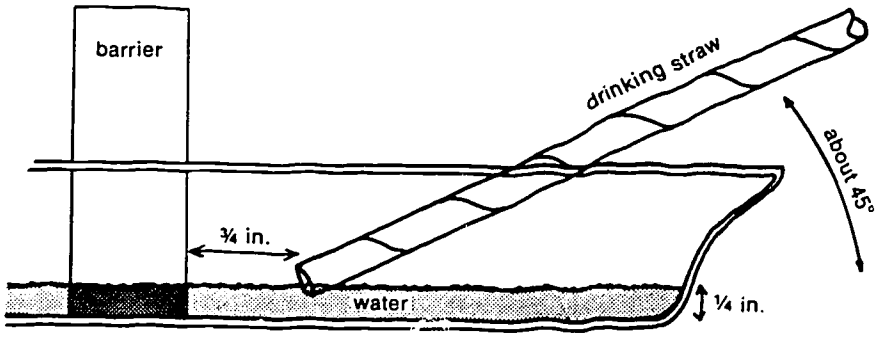


blowing steadily and gently through a drinking straw. Hold the straw at an angle with one end just touching the water. Direct your stream of air toward the point of the middle barrier. Carefully observe the pattern of overlapping waves beyond the barrier.

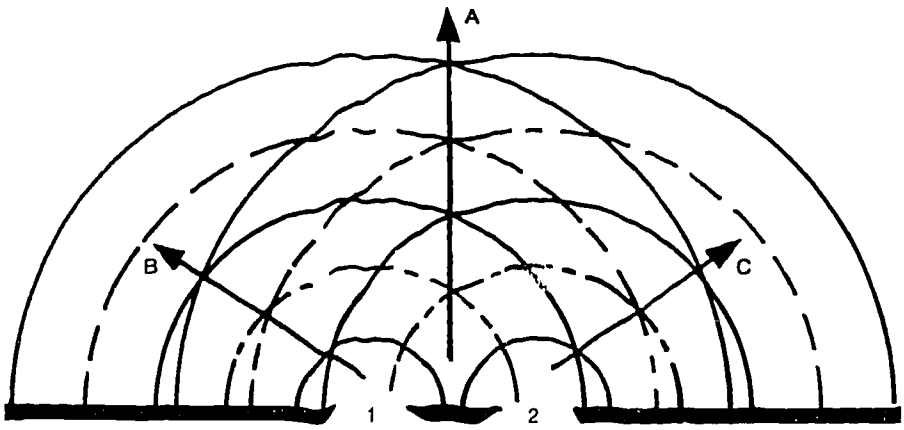




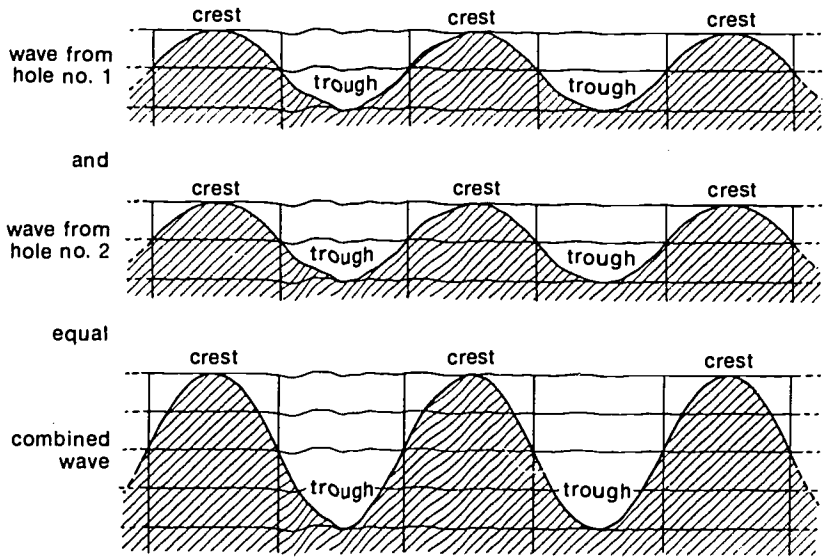

What really happens when water waves cross each other? The ripples in the tank are so small and moves so quickly that they can't be examined carefully. We need an instantaneous snapshot of the situation.




Look at the next diagram. The solid curves represent the crests of waves coming from each opening. The broken curves represent troughs. Look straight outward along line *A*. Notice what happens at each place you see a crest or a trough. Look outward along lines *B* and *C*.

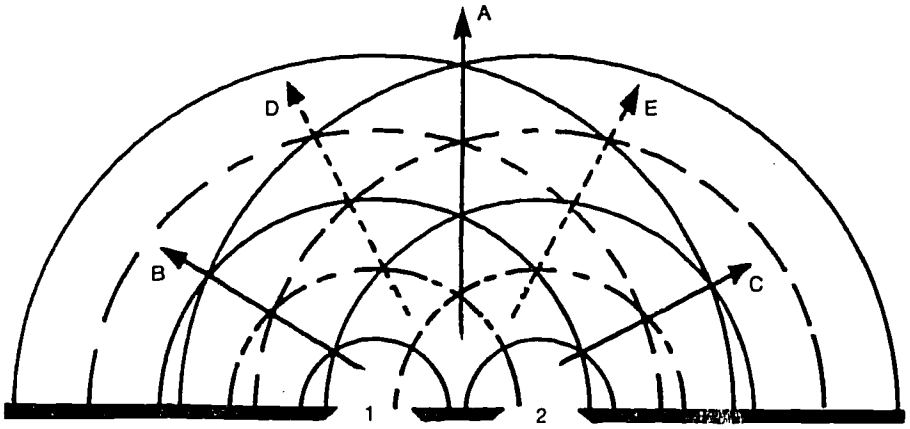



Along lines *A*, *B*, and *C*, you will see two crests or two troughs meeting. Suppose the waves coming from each opening have crests one foot high. How high would the combined crest be? If the troughs are one foot deep, how deep would the combined trough be? The drawing below helps explain how crests and troughs reinforce each other to construct bigger waves. This is called *constructive interference*.

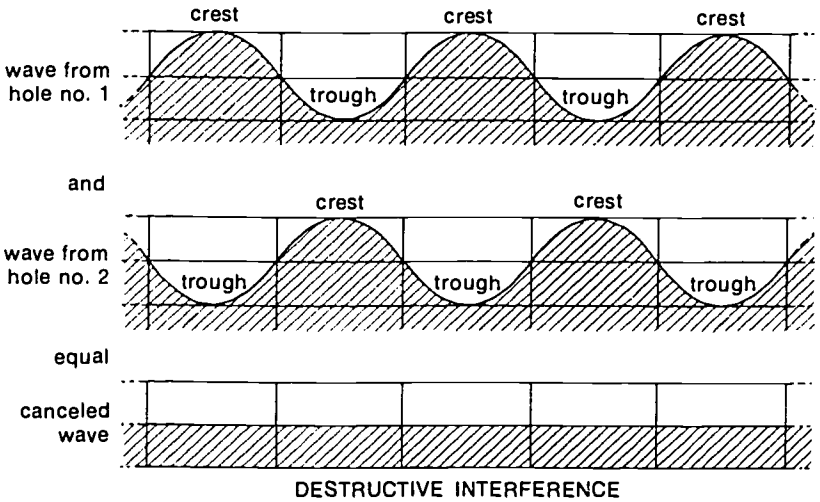



CONSTRUCTIVE INTERFERENCE

Look again at a ripple diagram. This time refer to the diagram at the top of page 28. Look outward along the dotted lines *D* and *E*. What happens at each place you see a crest or a trough?



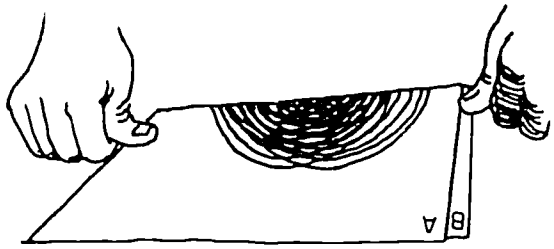

Along lines *D* and *E*, each time you see the crest of a wave coming from one hole you also see the trough of a wave coming from the other hole. You are on a crest and in a trough at the same time. What occurs when crest meets trough? Suppose each wave has crests one foot high and troughs one foot deep. The drawing below helps explain how crests and troughs cancel or destroy each other. This is called *destructive interference.*



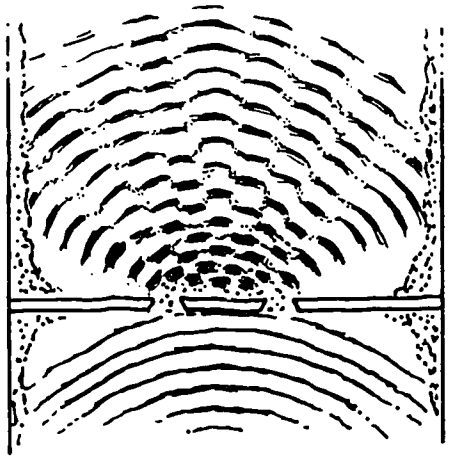

DESTRUCTIVE INTERFERENCE

Examine Plates *A* and *B*. (These and other plates for these activities will be available from your teacher.) The curved lines represent crests of waves that radiate away from the dot at the barrier hole. Troughs lie midway between the curving crests. Turn Plate *A* over so that you are looking at it from the reverse side. Fit

it on Plate *B* so that the base line and vertical mark on *A* coincide with the base line and vertical mark on *B*. Look down on the plates from a distance. Notice the pattern of light and dark bands. Light paths show where crests cross each other; dark paths show where crests and troughs cross.



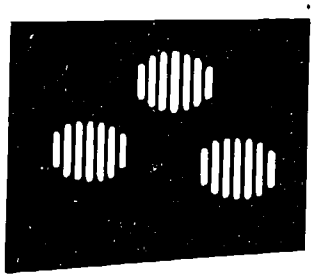

Look again at the wave pattern of interfering ripples. Use the ripple tray with the two-hole barrier. Blow gently and steadily through the straw. Look carefully at the wave pattern. Try to identify the paths of destructive interference, where there are no waves. Look at the paths of constructive interference, where there are strong waves.

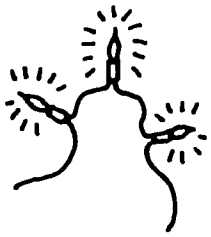


Here is another example of how waves and particles behave in different ways. Particles go through two holes in straight lines. Waves interfere to produce paths of strong waves and paths of no waves.

## THE CRUCIAL EXPERIMENT

So much for buckshot and ripples. What about light itself? Send light through two small holes. Will it behave as particles or waves? If light behaves as particles, what would you expect to see? If it behaves as ripples, what then? How would you identify a path of no light waves? Let's see how light behaves.



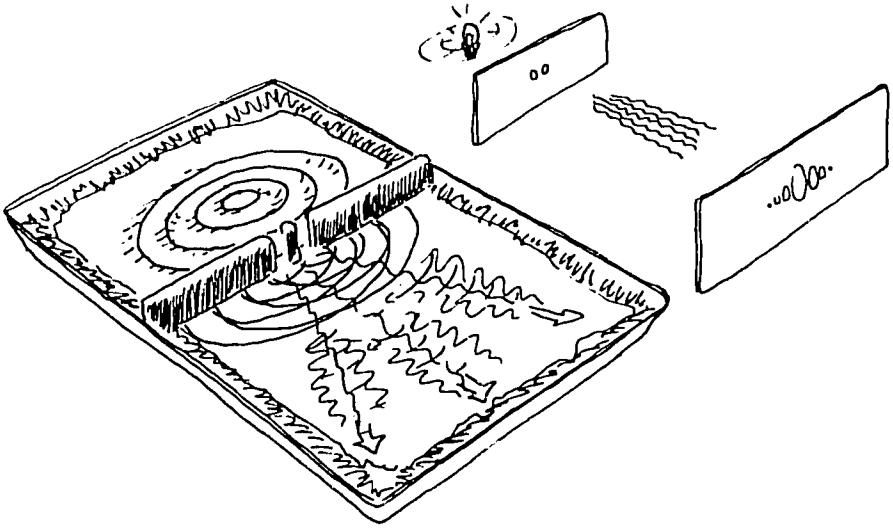


Use a sharp pin to make a pair of tiny holes in a piece of heavy paper about two inches square. Make the holes as small and as close together as you can. Peer through the holes at the tiny light bulbs you used before. Stand at least ten feet away from the bulbs. Rotate the card as you look. Describe what you observe about the light coming through the holes.

Does your observation of the interference of light correspond to the interference of waves in the ripple tray? Your source is no longer waves caused by air from a straw, but is light from a bulb. Instead of openings in paraffin, your openings are now holes in a barrier of paper. Water waves pass through holes and interfere in the space beyond. Light passes through holes and interferes in the space between the barrier and your eye. You see bright bands where constructively interfering waves come to your eye. The paths of no waves lead to the dark places in between.

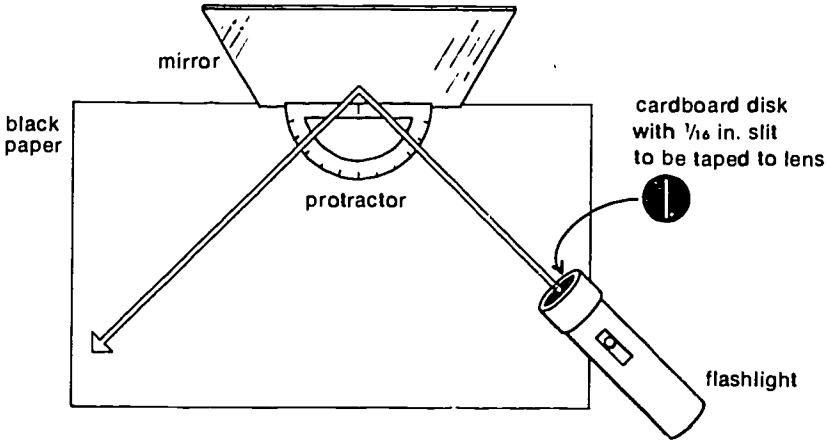
For explaining interference, the wave model works well, but the particle model does not. For explaining reflection and crossing light beams, these two models work equally well. As you will later see, there

are times when the particle model works better. Sometimes, however, neither model seems to do the job of explaining the behavior of light. For light is neither buckshot nor ripples. Light is light and nothing else.



## ON YOUR OWN

This activity shows how mirrors reflect light. Make a slit one-sixteenth of an inch in a circle of cardboard and tape the circle on the lens of a flashlight. Tape a flat pocket mirror upright along the end of a table. Place the edge of a protractor against the mirror

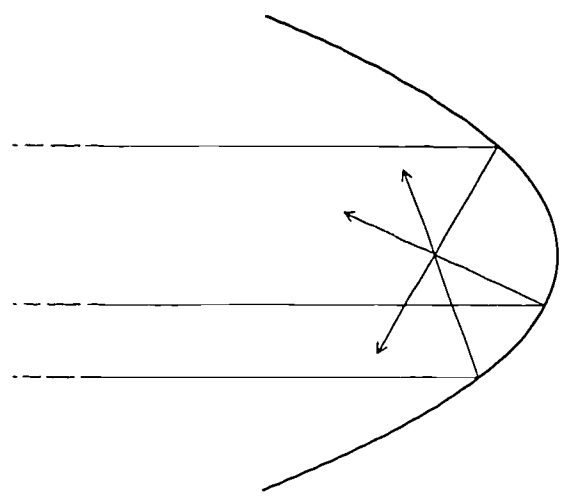


and slide black paper under the protractor. Darken the room. Hold the flashlight so that the vertical beam from the slit strikes the mirror at the center of the protractor. Hold the light close to the mirror. Read the angle where the beam crosses the protractor—the angle between the beam and the mirror. Also read the angle where the beam reflected from the mirror crosses the protractor.

Now move the light so that the beam crosses at 10°, then 20°, and so on. Read the angle of the reflected beam each time. Make a statement about how the angle of the incoming beam affects the angle of the reflected beam.

The clay barrier in this chapter is in the shape of a parabola. One interesting property of a parabola is that all parallel light beams, directly striking a reflector to this shape, are bounced back to a point. This point is called the focus of the parabola.

What would happen if a source of light were placed at the focus? What would the paths of the reflected beams be like?



CHAPTER 4

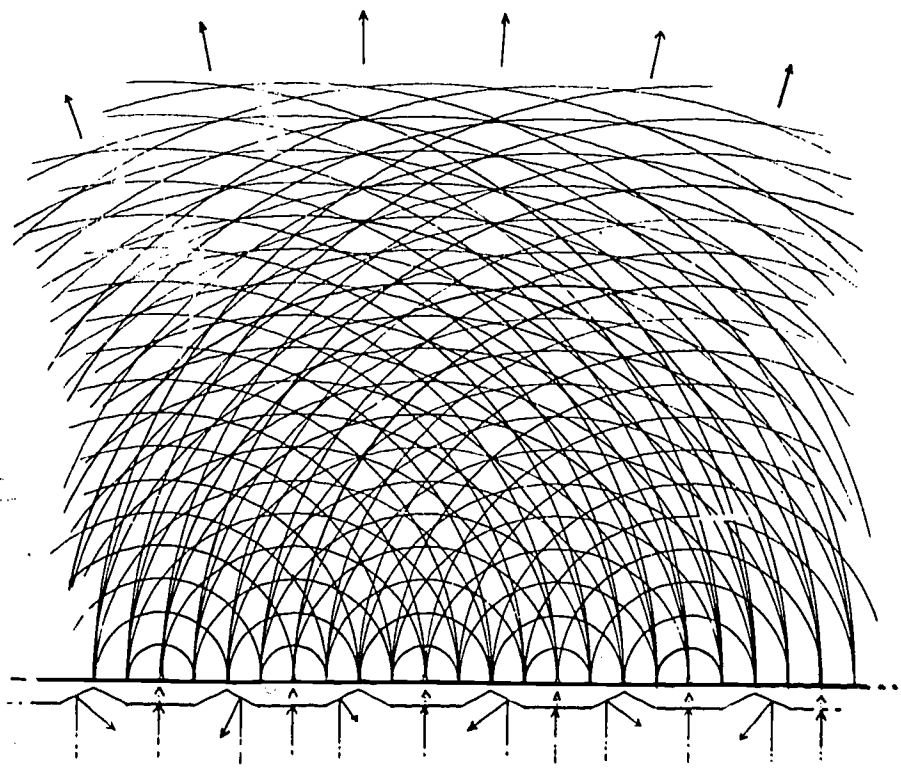
# The Electromagnetic Spectrum

One problem in seeing the interference of light through two pinholes is that the light is very faint. It would be better if we could use many more holes close together in a row. Then much more light could pass through.

Draw a straight line on a piece of paper. Using a sharp pin, make a row of ten tiny holes along the line as evenly spaced and as close together as possible.

Now look at the Christmas tree light bulbs through the row of holes. Do things look any different through a barrier with many holes than they did through a barrier with only two holes?

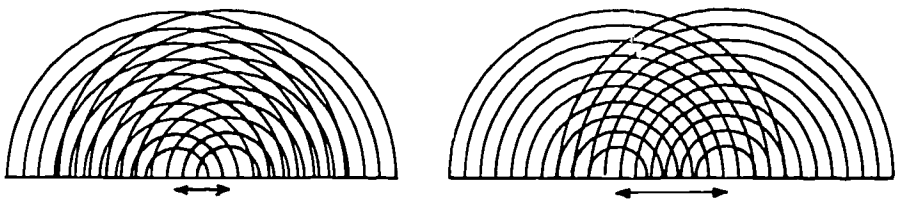
Many holes or slits let more light pass through. The interference pattern is therefore brighter than one seen with just two slits.



If you looked at a diffraction grating with a very powerful microscope, you would see thousands of grooves in the sheet of plastic. The spaces between grooves act like slits. Light can pass through them. A grating is like a barrier with many slits instead of just two. Refer to the diagram on page 33.

The slits in the plastic grating are very close together. What effect does the placing of the slits have on the interference pattern? Plates *A* and *B* will show you.

Turn Plate *A* over and place it on Plate *B*, so that the base lines coincide. This time move *A* horizontally across *B*. What happens to the paths of constructive interference as you move the slits closer together? As you move them farther apart? Remember that the waves on Plates *A* and *B* have the same wavelengths. How should you locate the slits on a barrier if you want the interference paths to spread out at wide angles? At narrow angles?



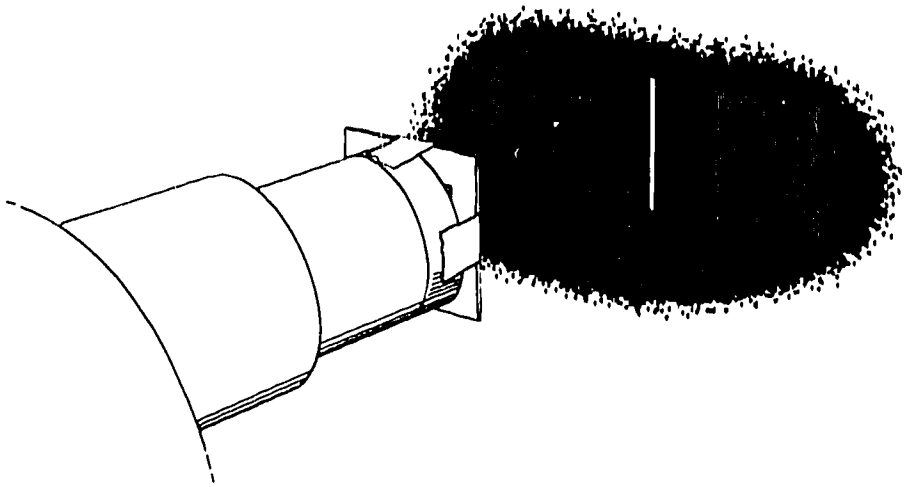
This activity shows that if the slits are very close together, the paths of constructive interference are spread much farther apart. The slits in the plastic grating are so close that 13,400 are crowded into one inch.

## LIGHT AND COLOR

Like water waves, light waves interfere with one another. Like water waves, light waves must have wavelengths.

But there is something new when light waves interfere: colors.

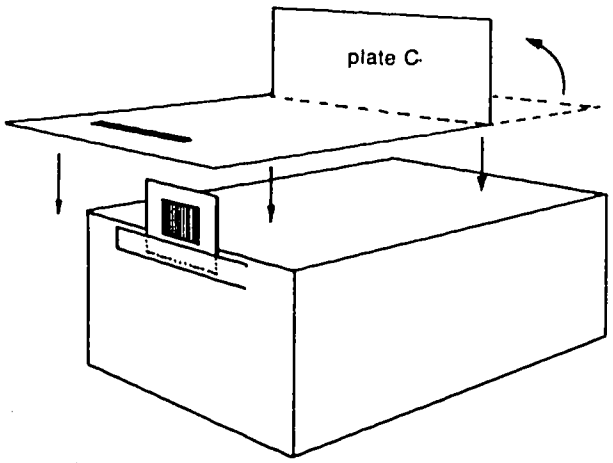
Make a 2 × 2-inch slide of cardboard with a long, narrow slit about one-sixteenth of an inch wide. Place it in a slide projector about three feet from a screen, and focus the image of the slit on the screen. Hold a piece of grating over the front of the projector. Turn the grating until the spectra are horizontal.



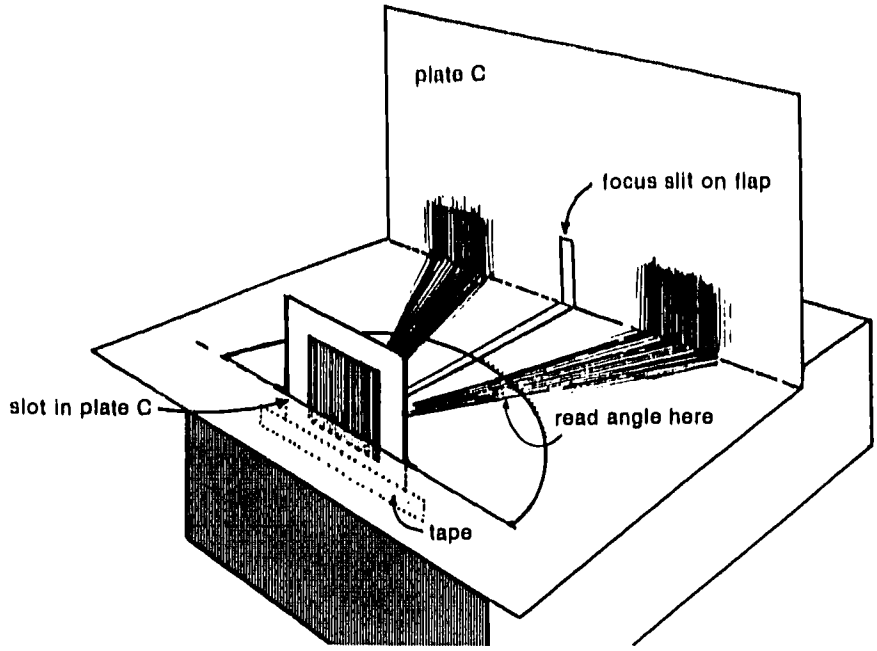
The whitish light from the projector contains light of all colors and is not a pure and simple thing. If you combined the colors of the spectrum, you would have whitish light back again. The light that reaches us from a flashlight bulb, or from Sirius, or from a slide projector is always a mixture of colors. You seldom see light that contains just a single color.

Can the wave model of light tell us anything about colors? Why they are spread out in a band? You can start to look for answers to these questions by carefully observing just how light of different colors behaves as it leaves the grating.

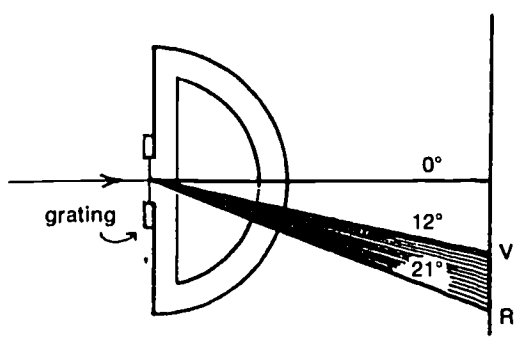
Mount the plastic grating on the end of an old book or box. Use tape. The grating should be level with the surface of the book. Cut the slot out of Plate *C*. Place Plate *C* on the book so that the mounted grating fits into the slot.



Once more place in the projector the 2 × 2-inch cardboard square with the slit cut into it. With the projector about two feet from the




grating, shine the narrow beam of light along the 0° line on the paper. Prop up the flap and focus the light on it. Adjust the projector so that the beams of colors can be seen along Plate *C*.

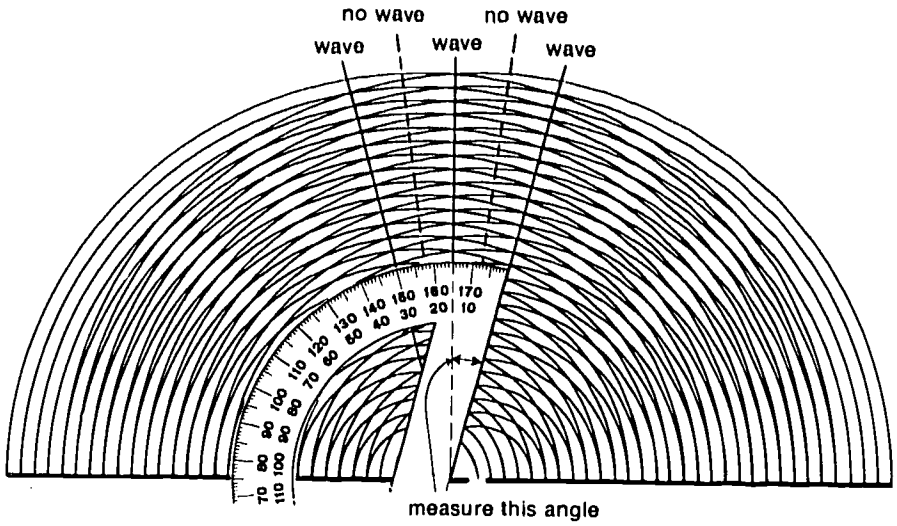



Look at each spectrum that emerges from the grating. Observe the angles that different colors of light make as they leave the grating.

In a table, record the colors found at each angle — 12°, 13°, and on through 21°.

Red light travels away from the grating in one direction, green light in another. Light of each color moves away in its own direction, and strikes the screen a little to the side of its neighbor to form the spectrum.

But why should waves of red light take a path different from green? Why don't all colors of light follow the same path and all strike the screen at the same place? Let us look at drawings of wave patterns again for clues.




The two interference patterns called Plates *D* and *E* are provided. They are drawn with different wavelengths, but the holes are the same distance apart on the two plates. What difference in the patterns of interference can be noted?

With a ruler, measure the wavelengths on each plate and enter the measurements in a table. On each plate measure the angle between the paths of constructive interference. Record the size of each angle next to the corresponding wavelength.

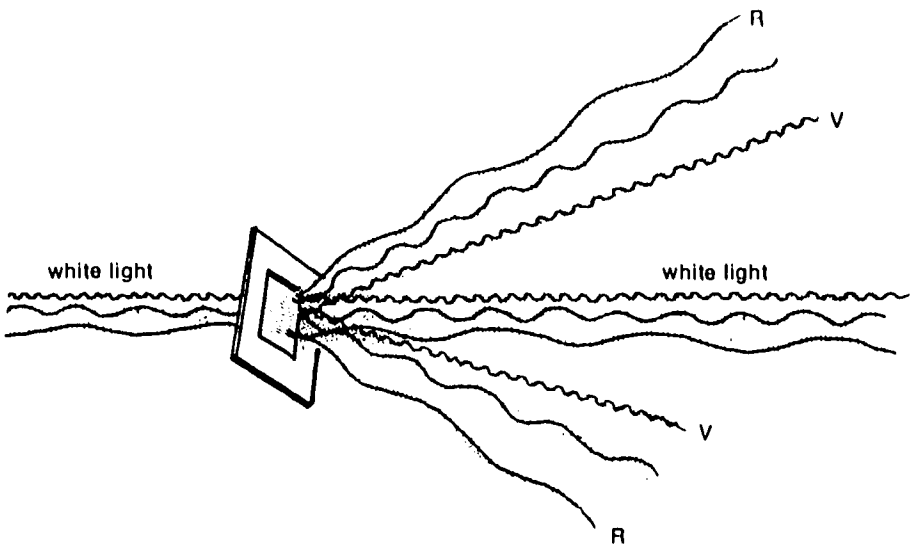
Which wavelength gives more widely spaced paths of waves? Tell how wavelength makes a difference in the interference pattern of waves and no waves.

Suppose that light with both wavelengths *D* and *E* is coming through one pair of slits at the same time. Light of wavelength *D* strikes the

screen in certain places. Light of wavelength *E* strikes the screen in certain places. Do they both strike at the same places?

Turn Plate *D* over and place it on Plate *E*. Make the holes coincide. Compare the paths of light. Where do you see only light of wavelength *E*? Where would you see light of both wavelengths *D* and *E* together?

The model predicts that if light behaves as a set of waves with a mixture of wavelengths, it will be spread into bands after passing through a grating. Each different wavelength will be separated from the others.




What can you now conclude about the wavelengths of red and violet light? Which are longer? As you "move" from the red end of the spectrum to the violet end, what happens to the wavelengths?

The white light coming from the projector is a mixture of light of many different wavelengths. After passing through a grating, light waves interfere and spread out according to their wavelengths. Violet light has the shortest wavelengths and red the longest.

## FINDING WAVELENGTHS OF LIGHT

Now you know that the wavelengths of red light are longer than those of orange light and blue wavelengths are longer than those of violet. But how long actually are these wavelengths? Again, drawings of wave patterns can show you how to find the answers.

Look at your measurements of the angles that different colors of light made as they left the grating. Which color moved away at 15°? We will now find the wavelength of this particular color of light, using Plate *D* to help.

You have already measured the wavelengths of the waves on Plate *D*. Now measure the distance between the barrier holes. What is the ratio of the wavelength to the distance between holes? The wavelength over the distance between holes equals what?

How many times smaller is the wavelength compared with the separation between the holes?

What would Plate *D* look like if it were shrunk to only half-size? The holes would be only half as far apart. Wave crests would also be half as far apart, therefore, the wavelength would be half as long. Changing the scale of the diagram, then, doesn't change the ratio of the wavelength to the distance between holes. You can prove this by measuring the new hole separation and wavelength on the half-size drawing.

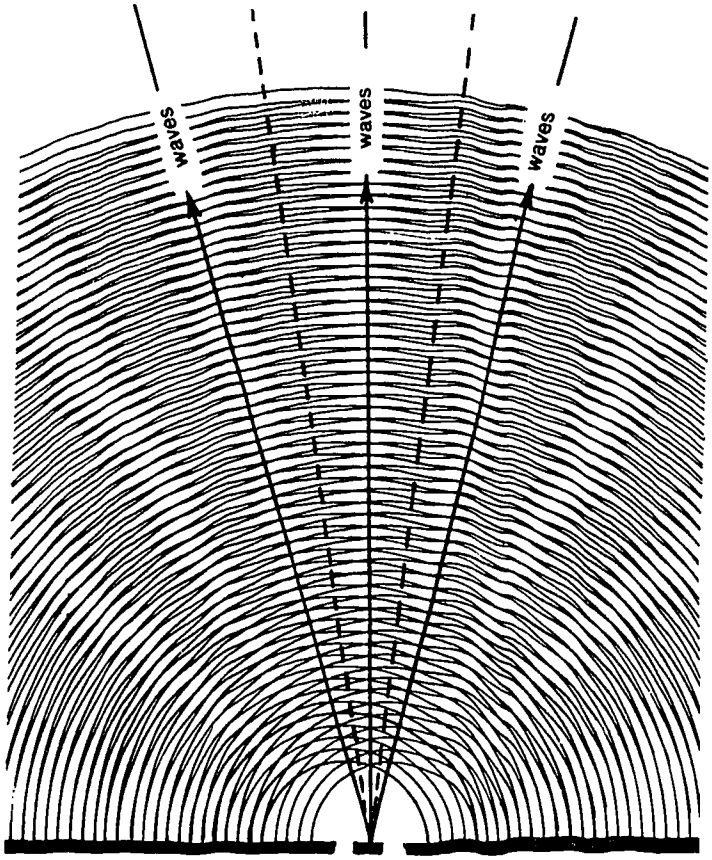
When you change the size of the diagram, what happens to the angles between the paths of constructively interfering waves? Check your guess by laying Plate *D* over the half-size drawing.

Enlarge or shrink Plate *D* as much as you wish, but two quantities always remain the same: the ratio of wavelength to distance between holes, and the angles between paths of constructively interfering waves.

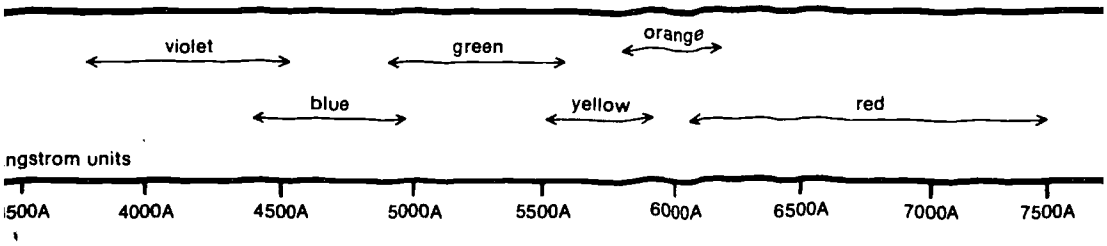
Here is a clue to finding the wavelength of the light that left the grating at 15°. Your measurements have shown you that there is also a path of constructively interfering waves at 15° on Plate *D*. Then you can think of Plate *D* as a greatly enlarged model of the grating and light waves. Plate *D* shows that the ratio is ¼ when the waves constructively interfere at 15°.

Once you know the distance between the "holes" in your grating, you can divide it by four and find the wavelength of 15-degree light. Since the plastic grating has 13,400 slits to the inch, the distance between "holes" is $\frac{1}{13,400}$ inch. The wavelength of the 15-degree light is four times smaller than this: $\frac{1}{53,600}$ inch.

Scientists have been able to measure the wavelengths of light by measuring the angular directions followed by light of different colors




after the light has passed through a grating. The wavelengths are extremely small. Red light has wavelengths of about $^{1}/_{36,000}$ inch. The wavelengths of violet light are near $^{1}/_{63,000}$ inch. It would take about 36,000 crests of red light or about 63,000 crests of violet light to form a train of waves one inch long.



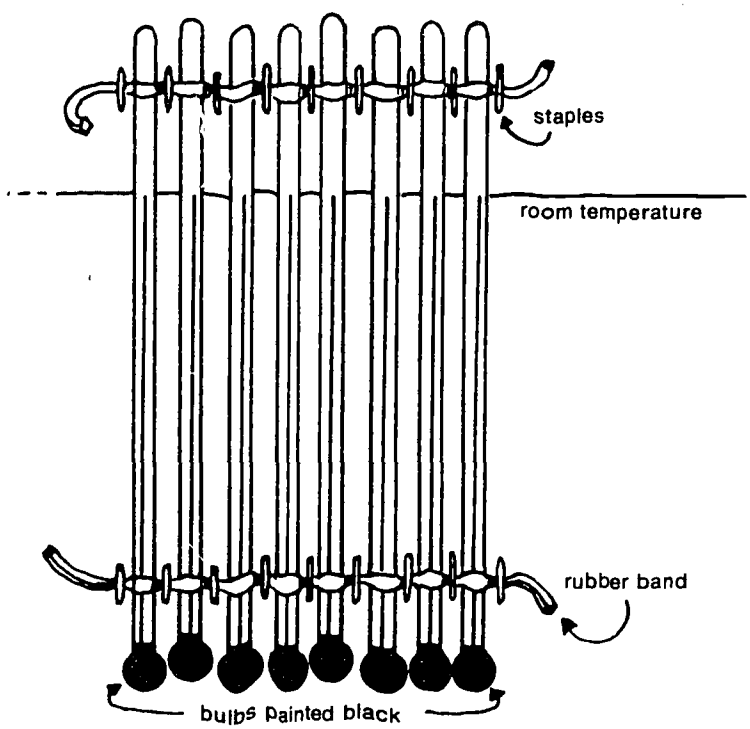

The inch is an inconveniently large unit to use to indicate wavelengths of light. When scientists measure extremely large or small quantities, they use different units. One of the units for wavelengths is called the

*Angstrom* (ANGH-strum) unit. The letter A is the abbreviation for the Angstrom. Red light has wavelengths of about 7000 A; violet, about 4000 A.

## BEYOND THE RAINBOW

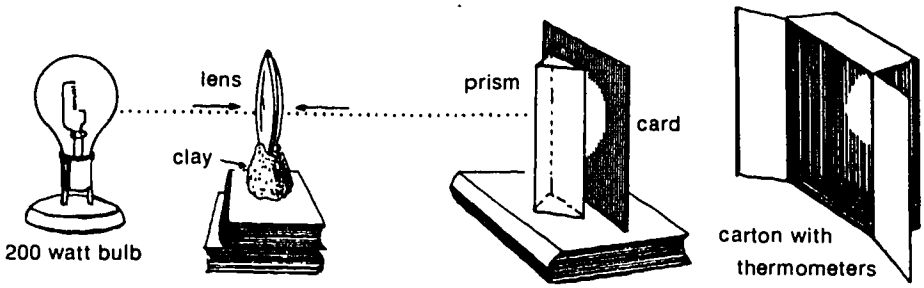
Are there any wavelengths shorter than violet light? Are there any longer than the longest red wavelengths that you can see? How could you detect waves that are invisible to your eyes?

Paint the bulbs of eight identical alcohol thermometers with dull black paint. Cut two rubber bands and staple them to a piece of cardboard, as shown in the diagram below. Draw a horizontal line between the two rubber bands. Insert the thermometers in spaces

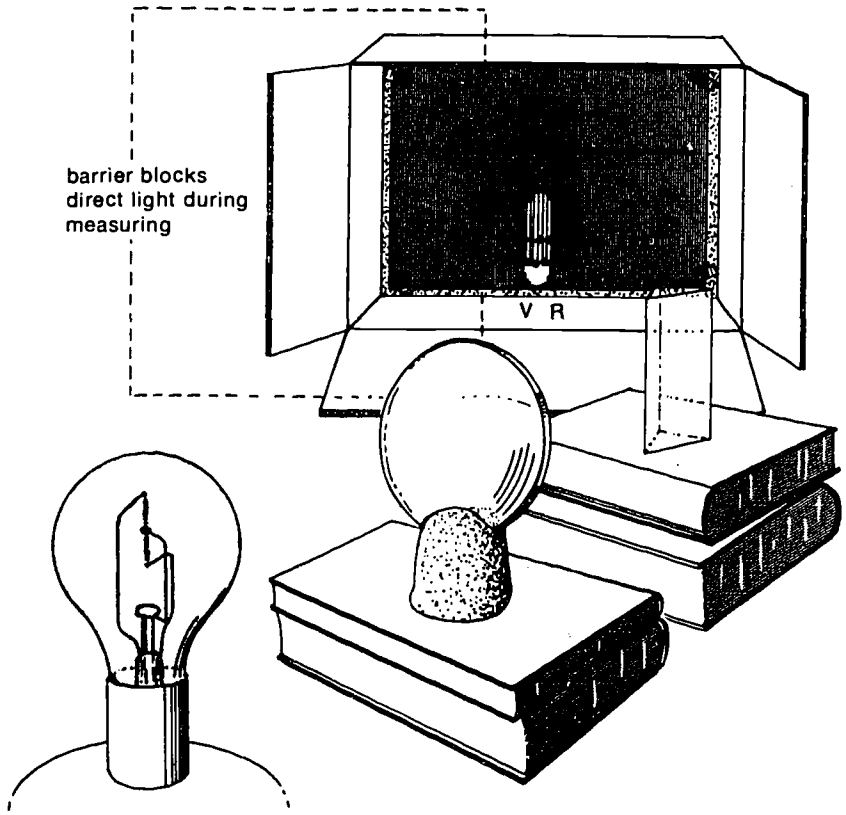



beneath the rubber bands so that the top of each alcohol column is just at the line. This line represents room temperature. Now tape the cardboard and thermometers to the inside of a small carton.

Place a 200-watt clear bulb about three feet from the carton. Mount a three-inch magnifying lens level with the filament of the bulb. Focus a clear image of the filament on the inside of the box by adjusting the position of the lens either closer to or farther from the bulb.




Hold a white card between the lens and the box. Move the card until the spot of light is about the same width as the 60° prism. Place the prism upright at this location with one angle pointing toward the light. The prism must be level with the lens. Remove the card. A spectrum will be directed out of the prism to each side.



Now position the carton so that the left-hand spectrum falls on the thermometers. Rotate the prism slightly until the spectrum is clear and sharp. One of the middle thermometers should be just within the red region of the spectrum, but the next one should be outside the red. Place a barrier beside the box to prevent direct light from striking the thermometers.

Turn the lamp off and allow the thermometers to cool to room temperature. Adjust the thermometers if the alcohol columns are not even with the line.

Turn on the light and do not disturb the apparatus for 10 minutes. Now read the thermometers. Which thermometer records the highest temperature? Did the focused visible light from the filament fall on this thermometer?

Something caused the temperature in the zone just beyond the band of red to rise. Something besides visible light traveled from the bulb, was focused by the lens, passed through the prism, and fell on the thermometers.

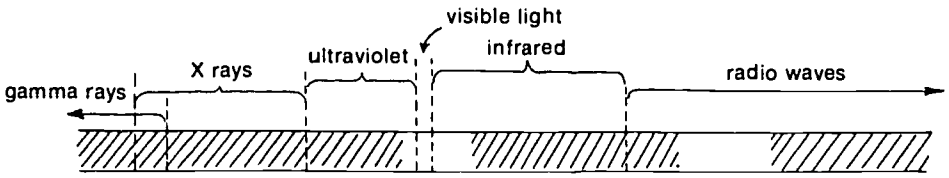
You have detected radiation that is redder than red. The bulb radiates more than the light you can see. Beyond red light there are longer wavelengths called *infrared* radiation. Although our eyes cannot respond to it, thermometers do respond. Infrared radiation includes a wide band of wavelengths from 7500 A to about 10,000,000 A, or 1 millimeter in length.

Thermometers cannot detect wavelengths longer than infrared. These longer wavelengths are radio waves and radio receivers are needed to detect them. Radio waves from broadcasting antennas move through the atmosphere to your antenna. Your radio is sensitive to wavelengths of 150-160 feet—much longer than the very short wavelengths of visible light.

Radiation with wavelengths shorter than violet light is called *ultraviolet*. The wavelengths of *X-ray* radiation are shorter still. *Gamma* radiation has the shortest wavelengths of all.

As you will find in a later chapter, radiation with wavelengths much shorter than violet cannot penetrate the earth's atmosphere. Astronomers must send instruments aloft in rockets and man-made satellites if they are to record the ultraviolet, X-rays, and gamma rays coming to us from the depths of space.

The entire band of waves, from the shortest to the longest, is called the *electromagnetic spectrum.* Your eyes respond only to a small part of this spectrum. There is more to the electromagnetic spectrum than meets the eye.




shaded areas show regions of spectrum blocked by the atmosphere

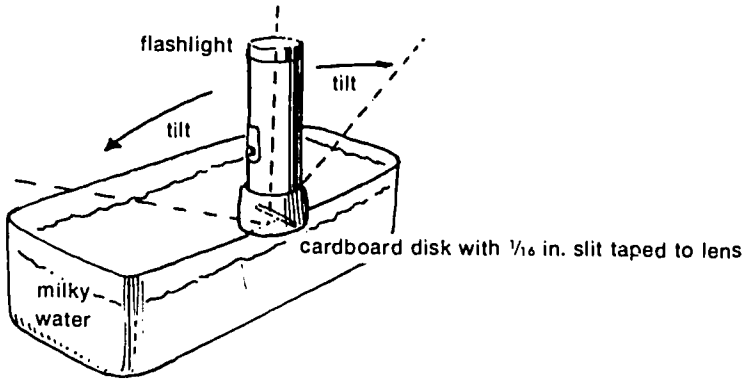
## ON YOUR OWN

A phonograph record can serve as a grating. But when you use it, you will look at light that is reflected off the record, rather than transmitted through it. Look at light from a lamp across the room. Hold the record so that the light strikes it at a glancing angle. The reflected light waves interfere exactly as transmitted light waves do.

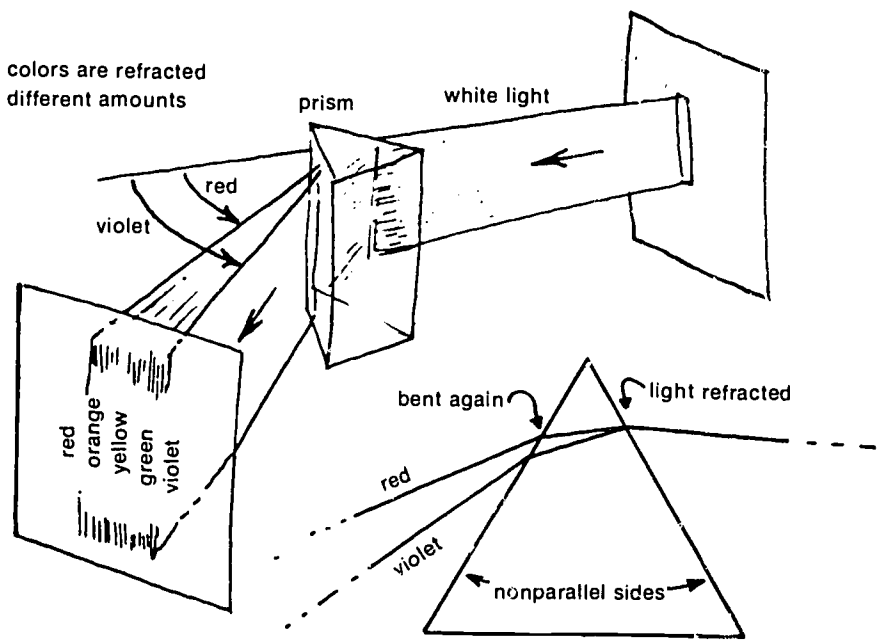
Make a slit one-sixteenth of an inch wide in a circle of cardboard and tape it on the lens of a flashlight. Fill a deep, transparent refrigerator dish almost to the top with water. Place a few drops of milk in the water. Rest the lighted flashlight on one rim of the dish so that the narrow beam shines directly down into the water. The beam should shine along the side of the dish. Now darken the room completely. Is the beam bent by the water when the light is shining straight down?

Now tilt the flashlight so that the beam strikes the water at different angles. Keep the flashlight resting on the rim. How does the angle affect the bending of the beam at the surface of

the water? In what direction is the light bent? The bending of light when it passes from one transparent substance to another is called *refraction.*




A prism spreads white light into a spectrum because the light is refracted as it passes through the glass. First the light is bent as it enters one side of the prism at angles. It is bent a

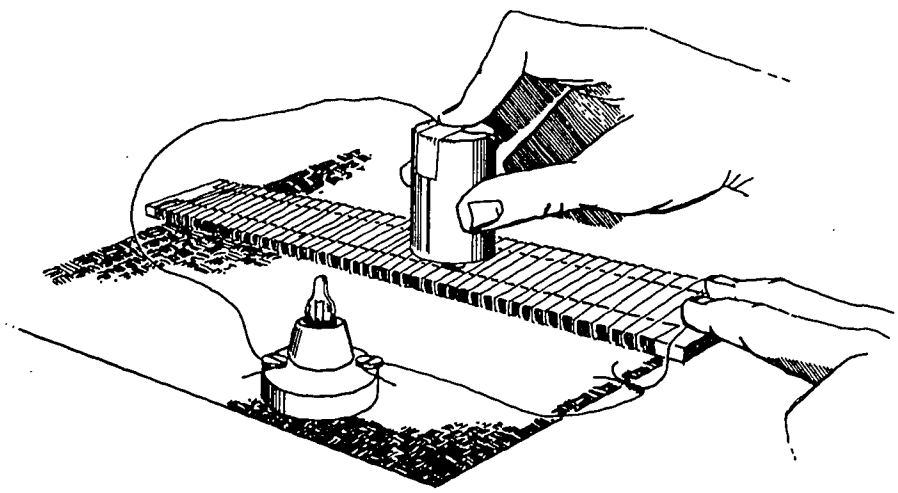



second time, and in the direction, as it leaves the prism because the exit surface of the prism is not parallel with the entrance surface. Longer wavelengths are bent less than shorter wavelengths: red is bent less than violet.

CHAPTER 5

# The Continuous Spectrum

Hot filaments of electric light bulbs radiate many wavelengths. The spectrum of their radiation shows all colors, with no gaps. It is a *continuous spectrum.* Can the continuous spectrum give any clues about the body that radiates it? Light bulbs appear to radiate only if they are hot. Let us begin our search for clues by looking for changes in the appearance of the continuous spectrum when the temperature of the source changes.



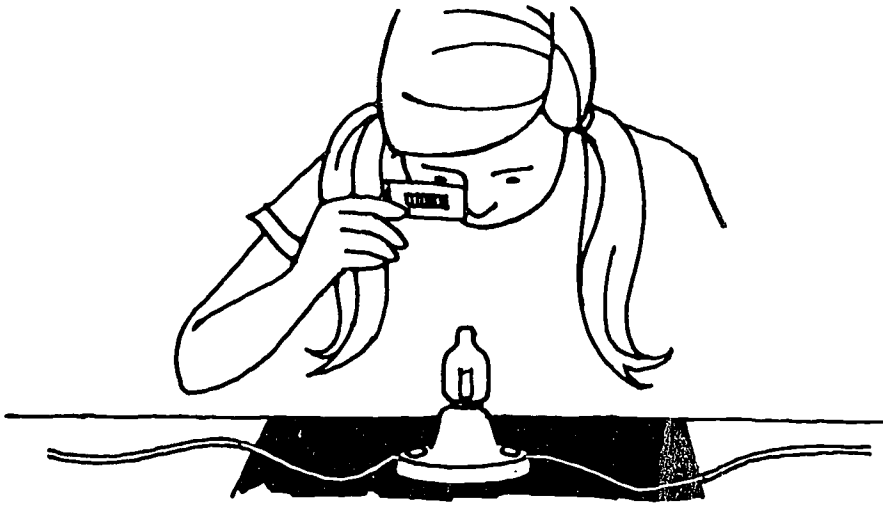
Place a strip of friction tape along each edge of a wooden ruler. Carefully wind about 12 feet of No. 30 uncoated steel wire around the ruler. The turns of wire must not touch each other. Tape both ends of the coil so that it will not unravel, but leave about two inches free on one end of the coil.

Wire a 1.5 miniature bulb in a socket. Connect one wire from the socket to the free end of the coil. Tape the other wire securely to the base of a flashlight cell with electrician's tape. Regulate the current through the bulb by inverting the cell and sliding the top contact across the coil. Darken the room as much as possible and observe the light from the bulb.

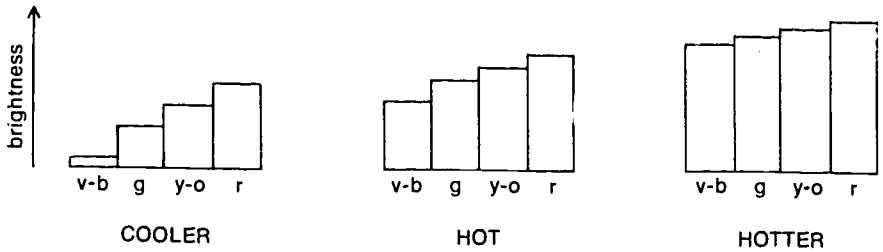
47

As more current goes through the bulb, the filament grows hotter and the light it emits becomes brighter. As the current decreases, the filament becomes cooler and its light grows dimmer. The brightness of the light depends on the temperature of the filament.

Now observe the light through a grating. To make the spectrum easier to see, place a piece of black paper so that it makes a dark background for the spectrum. To eliminate stray light, cup your hand around your eye.

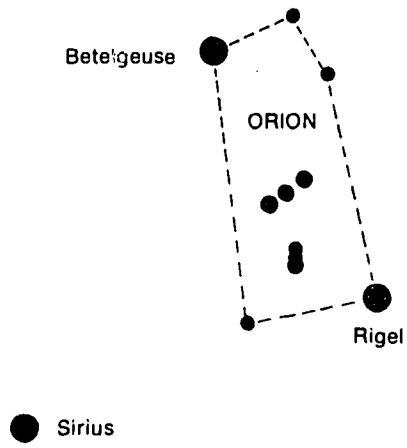


Examine the spectrum carefully when the bulb is brightest. Do the color zones seem equally bright? Lower the current slightly. Are all colors as bright as before? Decrease the current bit by bit.

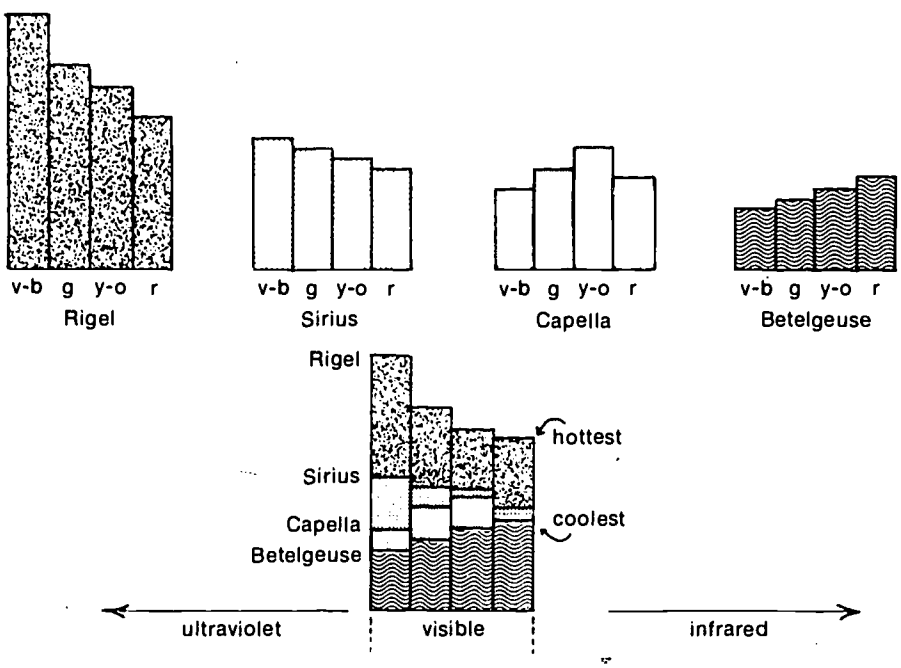



Are any colors fading more than others? What colors remain when the spectrum is barely visible? Now observe the changes again, starting when the bulb is dimmest and coolest. Describe how the spectrum changes as the temperature of the filament changes. These changes can be illustrated roughly with the type of graph shown above.

You have seen that cooler objects radiate most of their light in the red region of the spectrum. As the temperature is raised, more and more blue is evident. Can these ideas lead to a better understanding of the stars?




Betelgeuse (BET-'l-jooz) is the bright red in the winter constellation Orion (oh-RYE-un). Rigel (RYE-jul) and nearby Sirius appear bluish. Farther north in the winter sky, Capella (kuh-PELL-uh) shines yellow-white. Are the colors of these stars clues to their temperatures? Betelgeuse must be cooler because its radiation is mostly in the red or orange wavelengths. The bluish color of Rigel tells us that it must be hotter than Betelgeuse. What about Capella?



The color of Rigel suggests that it is the hottest of the four. It is so hot that the blue radiation is stronger than any of the other colors. Think back to your observations of the light filaments. As you made the bulb hotter, the shorter wavelengths became brighter. If you could have heated the filament to higher temperatures without melting it, the short wavelengths of blue and violet would at last have outshone the wavelengths of other colors. The colors of the stars give us a clue to their temperatures.

## PLANCK CURVES

So far, you have used only your eyes to detect radiation. But eyes see only the visible wavelengths. What are the other wavelengths doing as you raise the temperature of the radiating filament?

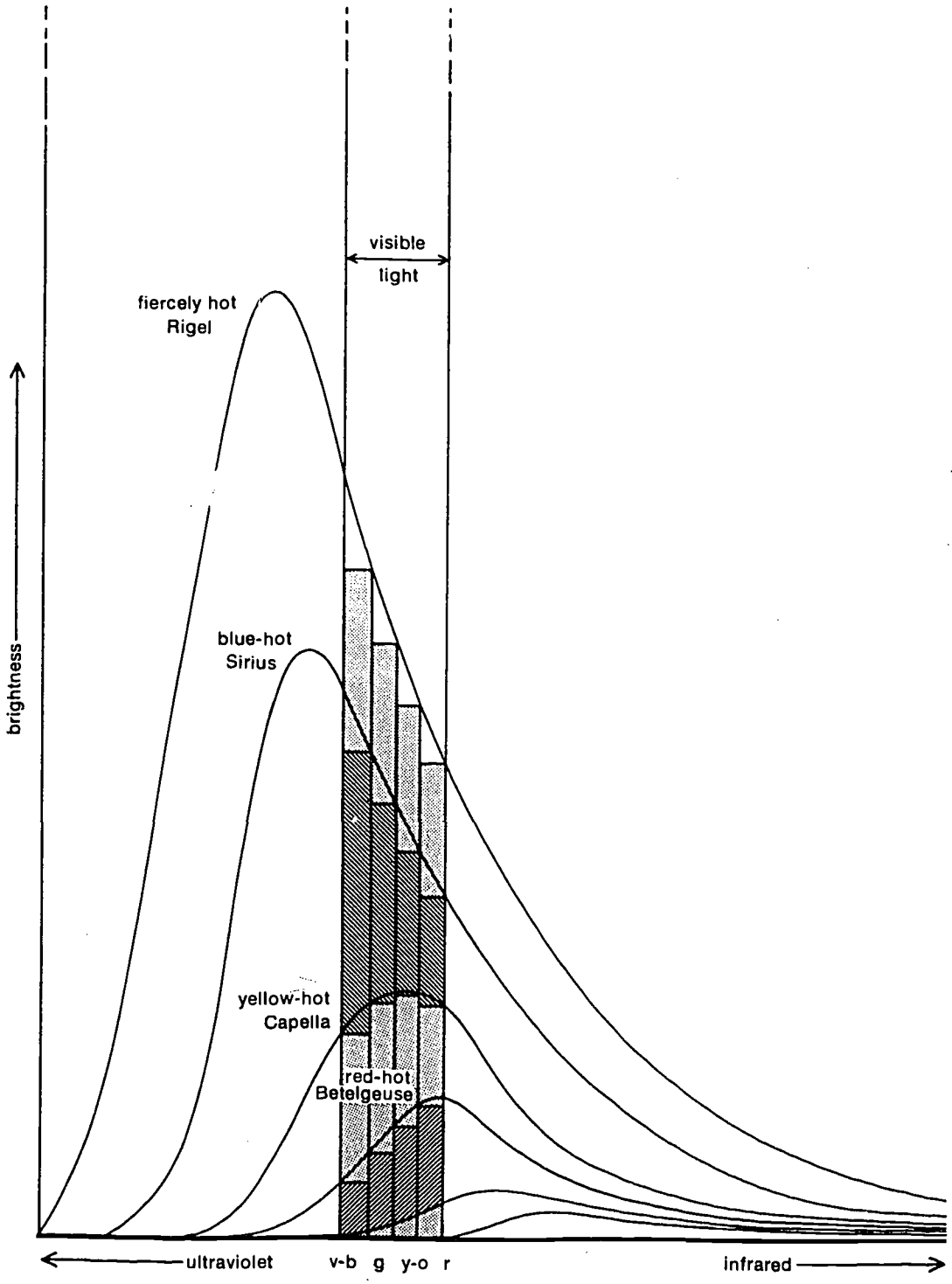
To find out, you would need detectors that can "see" in all the wavelengths throughout the electromagnetic spectrum. Heat detectors could be used in the infrared. Photoelectric cells could detect the ultraviolet and visual wavelengths. Radio receivers could measure brightness in the radio wavelengths. Physicists use a variety of detectors to measure the brightness of an object at every wavelength in the spectrum.

Graphs that show the brightness of an object's radiation at different wavelengths are called *Planck curves*, after the German physicist Max Planck (PLAHNGK). He was the first to offer a theory to account for these curves at about the year 1900.

Look carefully at the Planck curves in the diagram. There are many things to notice about the way the curves change as the radiating body grows hotter. Perhaps the first difference you notice among the curves is the great change in their sizes as the temperature rises. How does this agree with the way you observed the brightness of the light-bulb change in visible wavelengths?

What do the Planck curves show about the way the color of a radiating body changes as it grows hotter? Do the blue and violet wavelengths get brighter than the red? Radiation from extremely hot objects is rich in untraviolet and even X rays. The cooler objects emit too little radiation at these short wavelengths to measure.

Notice the point where each curve is brightest. How do the peaks of the curves differ? In what direction does the peak wavelength move as the radiating source becomes hotter?

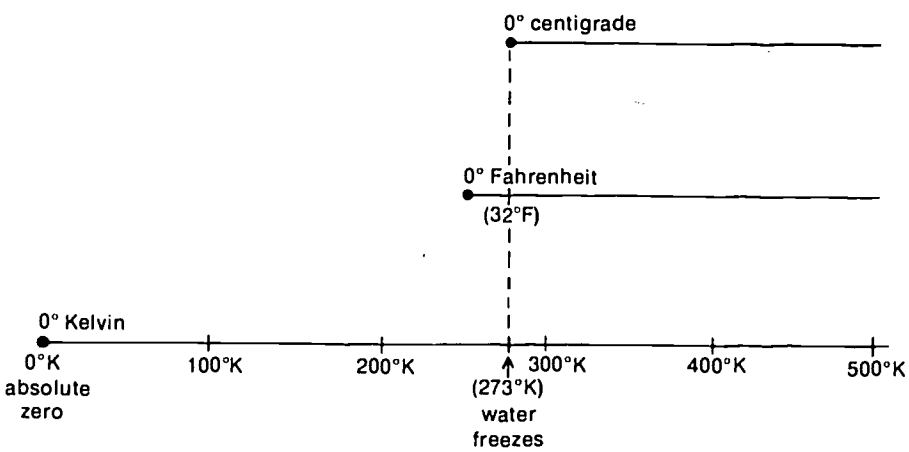

visible
light
fiercely hot
Rigel
blue-hot
Sirius
yellow-hot
Capella
red-hot
Betelgeuse
brightness
ultraviolet
v-b g y-o r
infrared

## ABSOLUTELY

If left to itself, a hot object will cool by radiating away its heat. The light bulb you were observing cooled down to the temperature of the room soon after the electricity was turned off. It could not have grown cooler than the room because its surroundings would then warm it back to room temperature. They are radiating too. At room temperature the bulb continued to radiate, but what it was giving up to its surroundings, the radiating surroundings were giving back at the same rate.

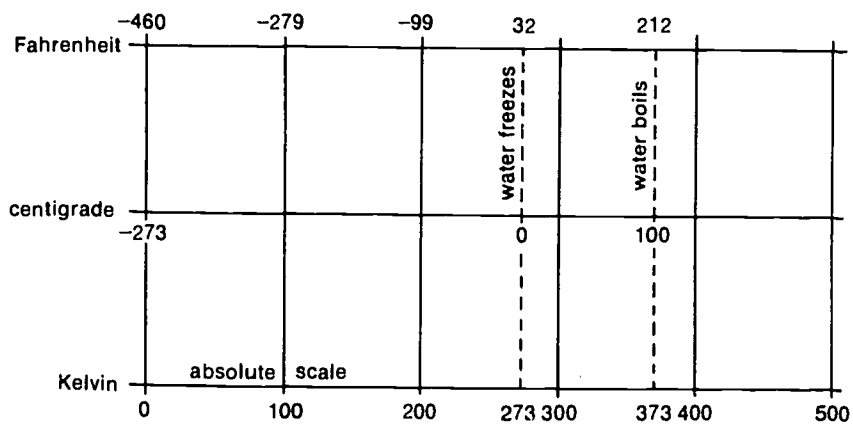
Imagine a light bulb suddenly extinguished out in the middle of nowhere, far from any person or object. It would radiate away its heat and its temperature would fall. As its temperature fell, it would radiate less and less brightly, and its radiation would occur mostly in the infrared and radio wavelengths. In time it would become so cold that its feeble radiation would diminish to nothing at all. It could grow no colder.

This thought experiment has led us to an extremely important idea about temperature. An object has fallen to its lowest possible temperature when it no longer has any heat to radiate away. Physicists call the temperature at which objects can no longer radiate *absolute zero.*




What is the temperature of absolute zero? Zero, of course. But it is not the zero most of us are familiar with. Many of our thermometers indicate Fahrenheit temperature. On these, water freezes at 32° and boils at 212°. On centigrade thermometers, water freezes at 0° and boils at 100°. But 0° C is certainly not absolute zero. Absolute zero, the temperature at which all radiation ceases, is −460° F or −273° C.

Scientists have found it convenient to use a thermometer that places zero at absolute zero and marks the degrees with the same scale used on the centigrade thermometer. Temperatures read on such a thermometer are given in degrees *Kelvin*. Water freezes at 273° and boils at 100° hotter—at 373° K.




## TEMPERATURE FROM COLOR

Temperature determines the characteristics of an object's continuous spectrum. How can you use the continuous spectrum as a themometer to tell the temperature of the body that radiates it? We have already talked about a method—observing the color of the radiation from the source. Now let's see how we can actually read this themometer in degrees.

Look at the Planck curves in the diagram on pages 54-55. You know how changing the temperature changes the brightness of one color compared with another. Suppose you compare the brightness at two wavelengths, say near 4000 A in the violet and near 7000 A in the red.

With just these two measurements you can learn the temperature of the source.

Use a millimeter ruler to measure the height of each curve at 4000 A and 7000 A. Record the measurements in a table. In the first column of the table enter the four temperature readings. In the second column record the height at 4000 A, and in column 3 the height at 7000 A.

You can now compare brightnesses at these two wavelengths for each temperature by finding this ratio:

$$\frac{\text{height (in mm) at 7000 A}}{\text{height (in mm) at 4000 A}} = \text{brightness ratio}$$

In the fourth column of your table enter the brightness ratio. Now can you think up a general rule that will describe how the brightness ratio changes with the temperature of the source?

Suppose you measured the brightness ratio for a star and found the ratio to be 2. What would you expect the star's temperature to be? What if the ratio were 1? Would the ratio for bluish Rigel be larger than 1?

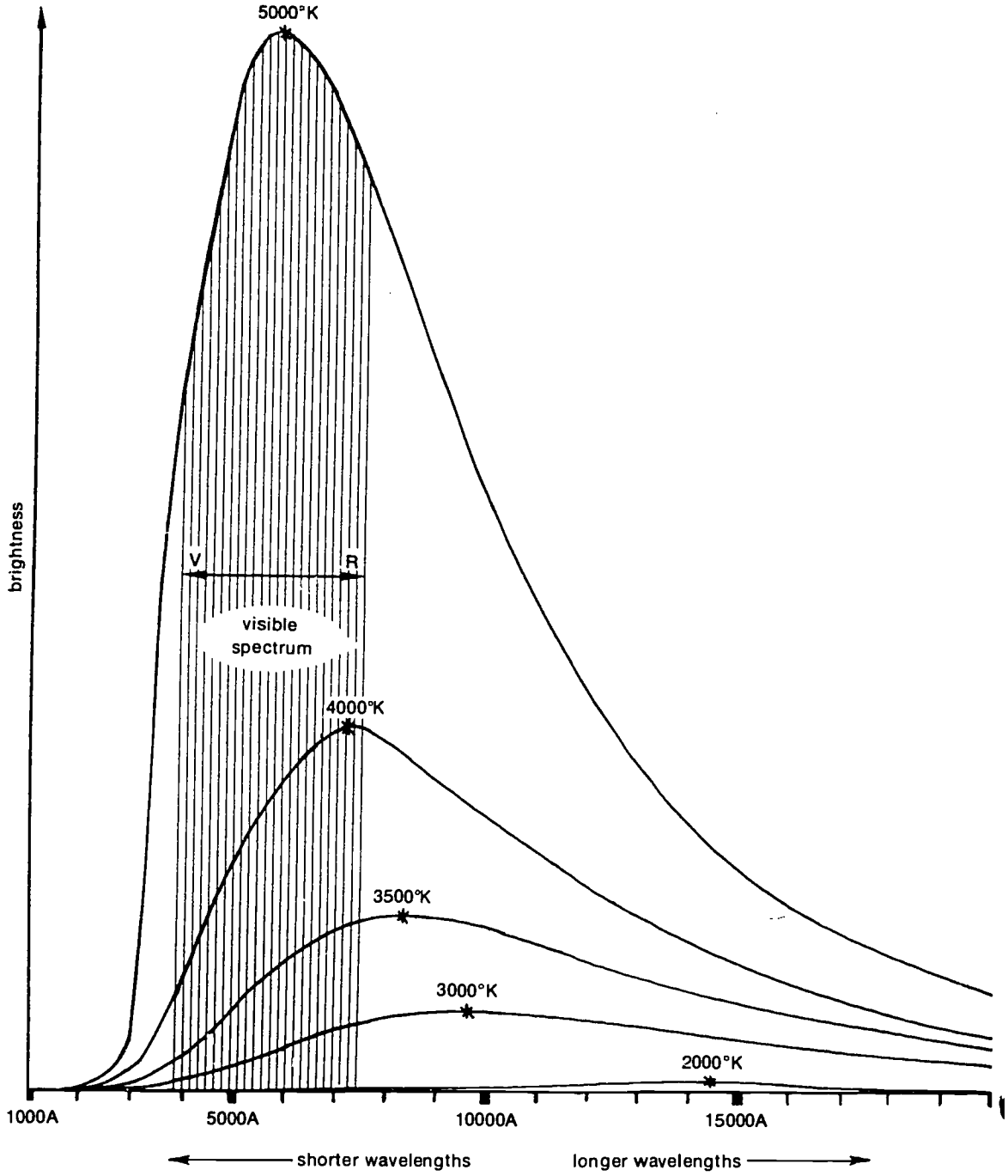
Can you see how the brightness ratio enables the temperature to be determined? Astronomers frequently find the temperature of a star this way. They call it the *color temperature* because they find it from the star's color.

## TEMPERATURE FROM PEAKS

The Planck curves show us another way to use the continuous spectrum as a thermometer. They show that the brightest wavelength changes with temperature. As we go to hotter sources, the highest part of the Planck curve moves steadily to shorter wavelengths. In the last century, Wilhelm Wien (VEEN) discovered that the peak wavelength multiplied by the temperature always came to the same number when he used Angstroms and degrees Kelvin for the units.

From the Planck curves, verify that Wien's relation is correct. Fill in a table with your results. Column 1 will show the temperature readings of 2000°, 3000°, 3500°, 4000°, and 5000° K. Enter the peak wavelength for each temperature in column 2. Calculate the product of the peak wavelength and the temperature of each case and enter the product in column 3. What is the nearest round number for the products you show?

How can we use Wien's law to determine the temperature of a star? Very simply. First, find the wavelength at which the continuous spectrum from the star is brightest. Then divide this number into 29,000,000. The result will be the temperature. For example, if the peak wavelength was 4000 A, the temperature of the source must be 29,000,000/4000, of 7200° K.

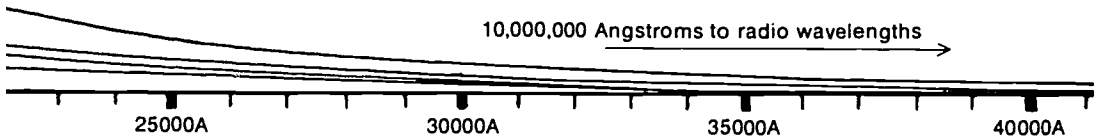

5000°K
brightness
V
R
visible
spectrum
4000°K
3500°K
3000°K
2000°K
1000A
5000A
10000A
15000A
shorter wavelengths
longer wavelengths

The peak of the Planck curve for the sun is at about 4900 A, in the green part of the spectrum. What is the temperature of the sun?

This method seems to be a very easy way to find the temperature of a star. Too often, however, the density of the earth's atmosphere keeps us from using it. Stars much hotter than the sun have their brightest wavelengths far in the ultraviolet. The atmosphere absorbs these wavelengths as they approach the earth's surface, and they do not reach us. We cannot observe the wavelengths at which hot stars have their greatest brightness. For these stars, we must rely on a brightness ratio to determine their temperatures.

Planck curves contain several clues which help us determine the temperature of the stars. We can determine temperatures from colors; we can determine temperatures from the peak of the curve. The following table gives some temperatures for stars determined from these relationships.

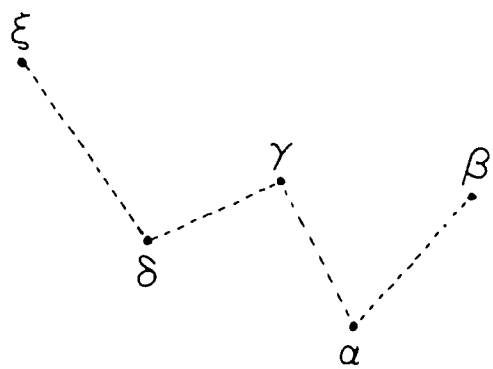
| *Star* | *Temperature (°K)* |
|---|---|
| Betelgeuse | 3,000 |
| Barnard's Star | 3,000 |
| Capella | 6,000 |
| Sun | 6,000 |
| Sirius A | 12,000 |
| Sirius B | 12,000 |
| Spica | 20,000 |



## ON YOUR OWN

Stars in a constellation are commonly named with Greek letters. Below is a diagram of the constellation Cassiopeia (KASS-ee-oh-PEA-uh). Also, in the table below, the peak wavelengths of each of the stars in this constellation. Using Wien's law, figure out the temperature in degrees Kelvin. Round it off to the nearest thousand degrees. Copy the table and fill in the blank spaces.

| *Star in Cassiopeia* | *Peak Wavelength (in Angstroms)* | *Temperature (°K)* |
|---|---|---|
| $\alpha$ (Alpha) | 5800 | |
| $\beta$ (Beta) | 4100 | |
| $\gamma$ (Gamma) | 1600 | |
| $\delta$ (Delta) | 3400 | |
| $\epsilon$ (Epsilon) | 1900 | |



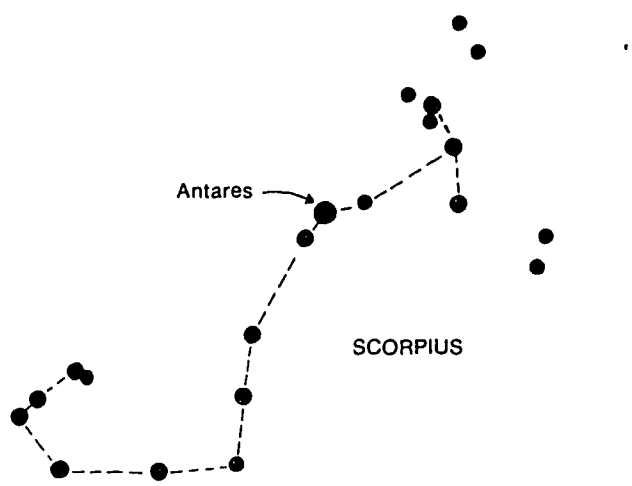
CHAPTER 6

# Trading Temperatures for Size

Stars commonly come in pairs. These *binary* (BYE-nuh-ree) *stars* can be found in great numbers in all parts of the sky. The two stars of a binary system are usually very close together. The members of a star-pair may be as close to each other as the earth is to the sun. For this reason the two stars attract each other with great force. They orbit each other endlessly.

Most binary stars appear only as a single star to the unaided eye. Only through binoculars and telescopes do they show up as two stars. Mizar (MY-zar), in the bend of the handle of the Big Dipper, is a binary. So is Albireo (al-BYE-ree-oh) in the constellation Cygnus (SIG-nuss) the Swan. A very interesting binary star is Antares (an-TARE-eez), the bright red star which appears in the constellation Scorpius (SCORE-pea-us). You can easily see Antares in the southern sky during the summer months.

Antares does not appear double to the unaided eye. But the telescope reveals that it has a faint blue companion star. Thus, Antares really consists of a very bright reddish star, the one you can see, plus a faint, hard-to-see blue companion. The red star is called Antares A; the other, Antares B. When astronomers determine the brightness ratios of these stars, they can find the temperature of each. The reddish star has a temperature of about 3000° K; the blue star is about 15,000° K.



An interesting fact is revealed when we measure the overall brightness of these two stars. The cooler one is sending us about 40 times as much radiation as the bluish one, even though the bluish star is hotter. How can we account for this observation? Why does the cool star send us more light than the hot star?

Distance could play a role. The farther away a radiating body is, the less bright it appears. Can Antares B really be far behind, appearing faint merely because it is farther away than Antares A? The answer is no. Antares is a binary star, and the two companions are each at about the same distance from the earth. Distance cannot be the answer to this brightness puzzle.

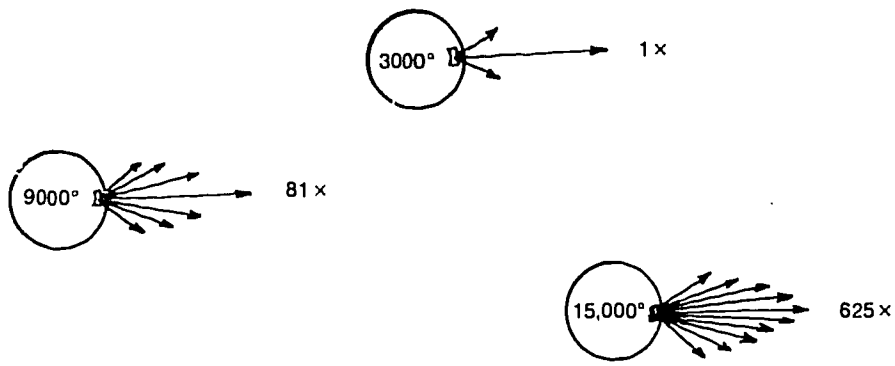
What else does a star's brightness depend on? We know that the higher the temperature of an object, the brighter it shines. Remember that as you increase the temperature of a light bulb, you increase the radiation emitted by the bulb. How much more radiation do you get when you double the temperature?

Careful measurements show that when you double the temperature of a radiating body, 16 times as much radiation comes out of the object through its surface. If you triple the temperature, the object emits 81 times as much radiation. This means that 81 times as much radiation must come out through each square foot of the object's surface.

| *Temperature increases by a factor of* | *Radiation increases by a factor of* |
|---|---|
| 1 | 1 |
| 2 | 16 |
| 3 | 81 |
| 4 | |
| 5 | |

The table above shows you a comparison between the radiation from a square foot of surface and the temperature. Copy the table and fill in the blank spaces. To do this, you will have to discover a rule that describes the relationship between the numbers. Here is a clue. What are the prime factors of 16? What are the prime factors of 81?

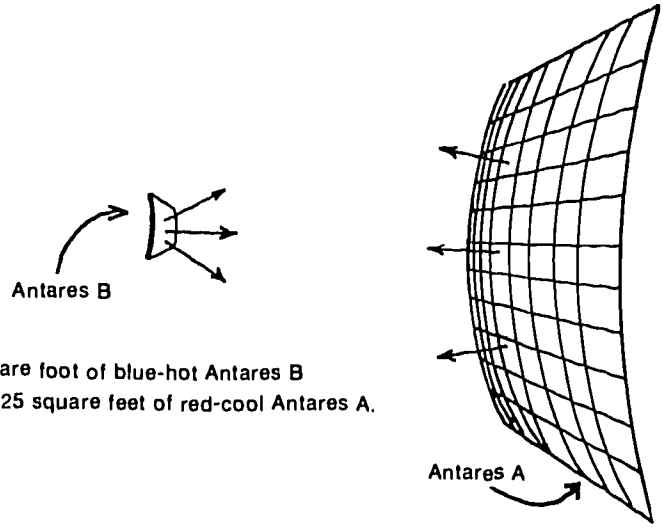
Astronomers make good use of the relationship that you have found. Stars are radiating bodies. The relationship shows how the radiation from each square foot of a star's surface changes as we look at stars with different temperatures.




Brightness ratios show that Antares A has a temperature of 3000° and its blue companion has a temperature of 15,000°. How many times as much radiation comes from each square foot of the hot star as from each square foot of the cool star?

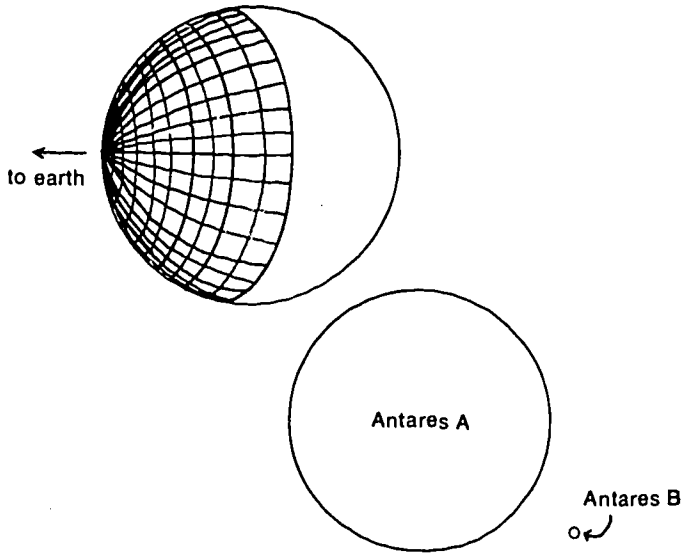
| | | |
|---|---|---|
| temperature of Antares A | = | 3000° |
| temperature Antares B | = | 15,000° |
| temperature of Antares B | = | 5 × temperature of Antares A |
| radiation from 1 square foot of Antares B | = | ? × radiation from 1 square foot of Antares A |

A square foot of Antares B emits 625 times as much radiation as a square foot of Antares A. Yet cooler Antares A is the brighter star. Obviously, temperature cannot solve our brightness puzzle. The temperature difference does not explain how the cooler star can outshine its hotter companion. We must look for something else to solve the puzzle.




One square foot of blue-hot Antares B
equals 625 square feet of red-cool Antares A.

When you look at a star, you see starlight emitted from all the square feet on the near side of the star. And the more square feet facing toward you, the more starlight you will receive.



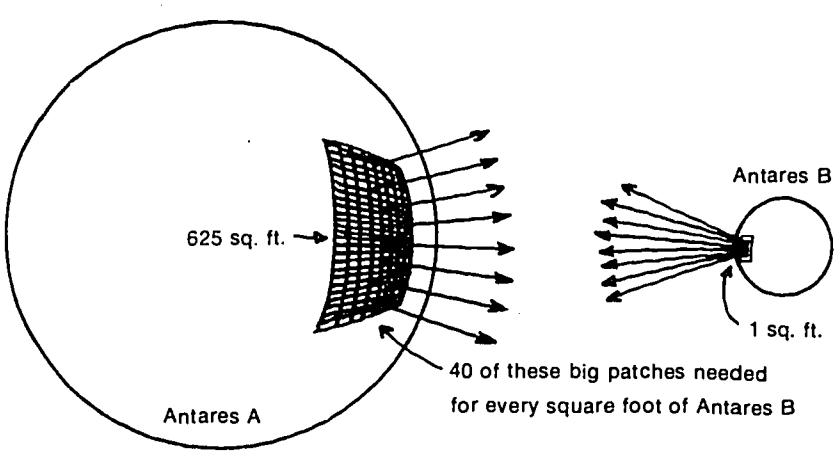

surface of Antares A = 625 × surface of Antares B

If we could give cooler Antares A enough square feet of surface, we could make its total radiation add up to more than that of Antares B, regardless of the temperature difference. Here may be the answer to the puzzle. A star's brightness must also depend on its surface area.

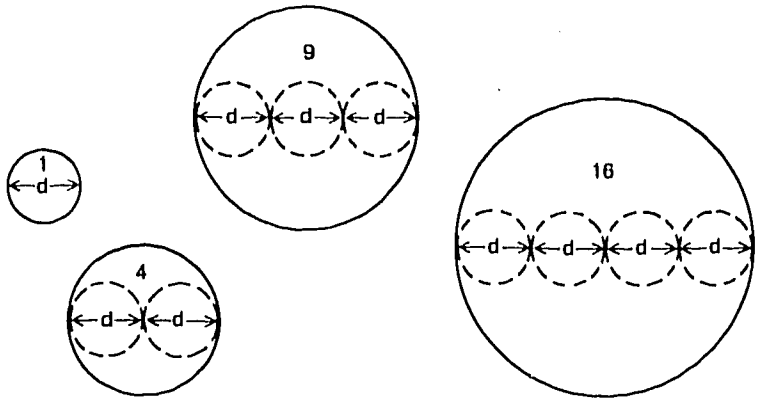
Suppose that the red star and the blue star of Antares were equally bright. How would the surface areas of the two stars then compare? For each square foot of Antares B, cool Antares A needs 625 square feet just to shine as brightly. The surface of Antares A would have to be 625 times as large as the surface of Antares B.

| | | | |
|---|---|---|---|
| IF: | radiation from 625 square feet of Antares A | = | radiation from 1 square foot of Antares B |
| AND: | total radiation from Antares A | = | 40 × total radiation from Antares B |
| THEN: | number of square feet of Antares A | = | 40 × 625 × number of square feet of Antares B |

Since the red star is actually much brighter—40 times as bright as the blue one—it must have an even larger surface to emit so much light. Let's determine how much larger Antares A is than its fainter sister star.




From your result, can you tell how the diameters of the two stars compare? If you double the diameter of a sphere, the surface becomes four times as large. Triple the diameter and the surface will have nine times as many square feet. Surface area increases with the square of the sphere's diameter.




You can use this rule in reverse. If the surface of one star is 25 times as large as the surface of another star, you can find out how the diameters compare. What number times itself equals 25? What if one star has 50 times as much surface as another?

Antares A has 25,000 times the surface of Antares B. Prove that the diameter of Antares A must be about 160 times as large as that of its small blue companion.

## ANTARES AND THE SUN

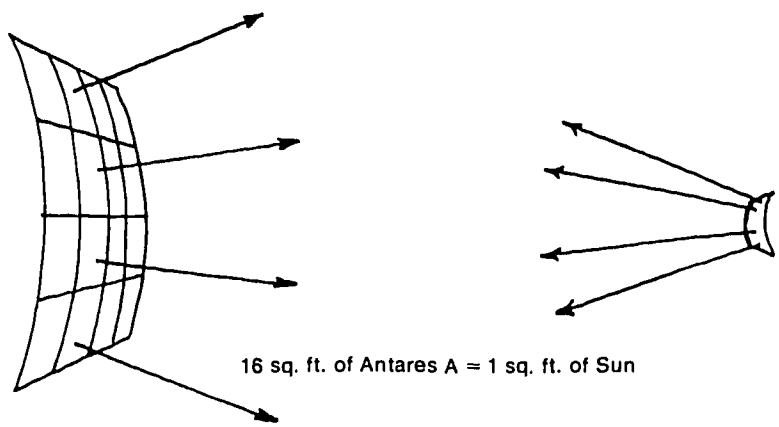
How do the diameters of the Antares pair compare with the diameter of the sun, the star we know best?

We were able to compare the orbiting Antares companions with each other because they are practically at the same distance from the earth. To compare them with the sun, we must imagine how the sun would appear if it were placed beside them.

Antares is about ten million times as far from the earth as is the sun. If the sun were moved to a position beside the Antares pair, the inverse-square law shows that it would fade to $1/10{,}000{,}000^2$ of its present brightness. Without a telescope, it would be lost from sight. In the telescope, Antares A would appear about 6400 times brighter than its new sun companion.

With the sun and Antares at the same distance, only temperature and size are left to explain why Antares A would outshine the sun. And since Antares A's temperature of 3000° is only one-half the temperature of the sun, Antares A must have a vastly larger surface than the sun.

| | | | |
|---|---|---|---|
| IF: | 2 × temperature of Antares A | = | temperature of the sun |
| THEN: | radiation from 16 square feet of Antares A | = | radiation from 1 square foot of the sun |




Antares A would need 16 times as much surface just to be as bright as the sun. But Antares A is actually 6400 times brighter. So the surface of Antares A must be vaster still.

| | | | |
|---|---|---|---|
| IF: | the total radiation from Antares A | = | 6400 × total radiation from the sun |
| THEN: | number of square feet Antares A needs | = | 6400 × 16 × the number of square feet the sun has |

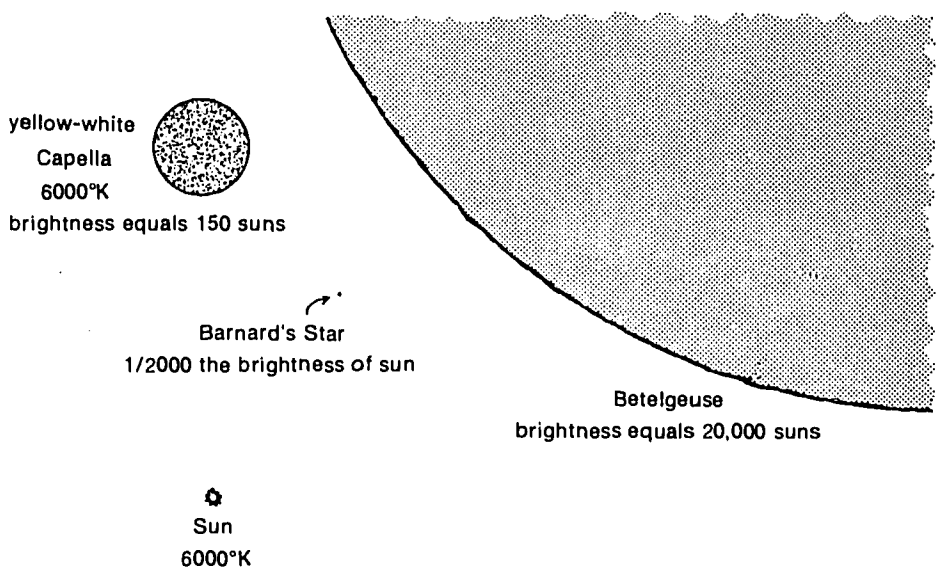
With a surface this big, the diameter of Antares A is about 320 times as large as the diameter of the sun. Prove it.

## OTHER STARS

A star's brightness depends on its temperature, size, and distance. The spectrum gives clues to its temperature. When the distance is known, the inverse-square law tells how bright the sun would appear if it, too, were at that distance. The star's temperature and brightness give the clues to the size of the star compared with the sun.

| Star | Temperature (°K) | Diameter (compared with sun) | Brightness (compared with sun) |
|---|---|---|---|
| Betelgeuse | 3,000 | 560 | 20,000 |
| Antares A | 3,000 | 320 | 6,400 |
| Barnard's Star | 3,000 | 0.09 | 0.0005 |
| Arcturus | 4,000 | 22 | 100 |
| Capella | 6,000 | 12 | 150 |
| Sun | 6,000 | 1 | 1 |
| Sirius A | 12,000 | 1.6 | 25 |
| Sirius B | 12,000 | 0.01 | 0.0025 |
| Rigel | 12,000 | 60 | 64,000 |
| Spica | 12,000 | 11 | 1,600 |

We can obtain the sizes and temperatures of many stars even though they always appear as pinpoints of light. Only the sun can be seen as a disk, but the message of starlight has told us much about the other stars.




## ON YOUR OWN

Recall the activity in which you determined the temperatures of the five stars in Cassiopeia. Refer to "On Your Own" on page 56. How much hotter than the sun is Gamma Cassiopeiae (KASS-ee-oh-PEA-ee)? Gamma's peak wavelength is 1600 A. Use 6000° K as the

sun's temperature. How much more radiation is emitted by each square foot of Gamma's surface than by each square foot of the sun's? Since Gamma is about 8100 times as luminous as the sun, how much more surface area must it have? Finally, how do their diameters compare?

| *Star* | sun | Gamma Cassiopeiae |
|---|---|---|
| *Temperature (°K)* | 6000 | |
| *Temperature (sun = 1)* | 1 | |
| *Radiation for each sq. ft. ($T^4$)* | 1 | |
| *Total Brightness* | 1 | 8100 |
| *Surface Area (sun = 1)* | 1 | |
| *Diameter (sun = 1)* | 1 | |

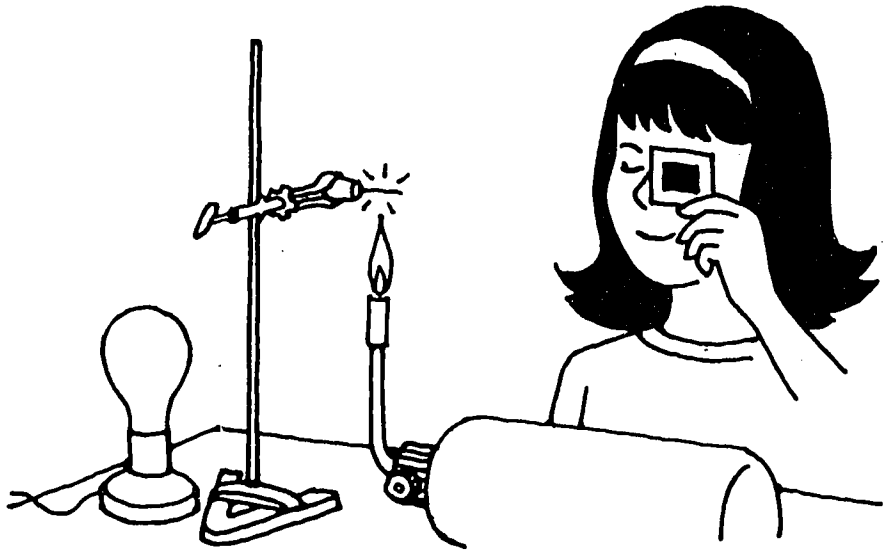
CHAPTER 7

# Emission Lines

The light of a star can reveal certain information about it. Even if a star is hundreds or thousands of light-years away, you can find its temperature by examining the continuous spectrum. If you can also determine its distance, you can learn its size.

You need to know more before you can paint a detailed portrait of the stars. From the continuous spectrum, can you learn what a star is made of?

Get several solids to use as sources of light—perhaps a paper clip, a strip of copper wire, and a piece of steel wire. Make each of these objects luminous by holding it in the flame of a gas burner. Each object emits a spectrum. Examine the spectra carefully. Are the spectra formed by these metals different from the spectra formed by light bulbs? Are they different from one another?

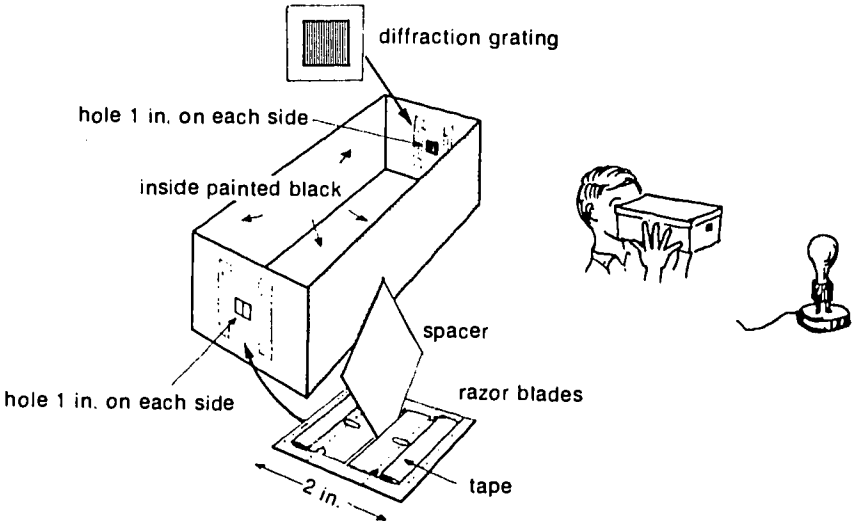


The continuous spectrum cannot reveal what a source is made of. The appearance of the continuous spectrum of any object depends only on the object's temperature—not on the material in the object. So you must look for another line of reasoning in order to find out what substances make up a star.

There are 103 known chemical elements. Some of them—such as iron, silver, and sodium—are solids. Others—such as hydrogen, helium, nitrogen, and oxygen—are gases. You can change solid sodium into a gas with little trouble. All you have to do is burn salt, which is a compound of sodium and chlorine. Iron can be vaporized—changed to a gas—if you can get it hot enough. Perhaps the characteristics of an element might be more apparent if we examine its spectrum when it is in gaseous rather than in solid form. To study such a spectrum, you need a spectroscope. Here is how you can build one.

Cut a one-inch-square hole in the center of each end of a shoebox. Both openings should be the same distance from the upper edge. Tape a grating inside the box over one of the holes, with the grating lines running up and down, so that spectra are formed from side to side. The direction of the grating lines can be determined by looking at a light source through the grating.

Make a mounting of a two-inch-square piece of cardboard. Cut a vertical slot in it one-fourth inch wide by one inch long. Tape a single-edge razor blade on one side of the vertical slit so that its edge is parallel with the slit. Cut a strip from an index card. Hold

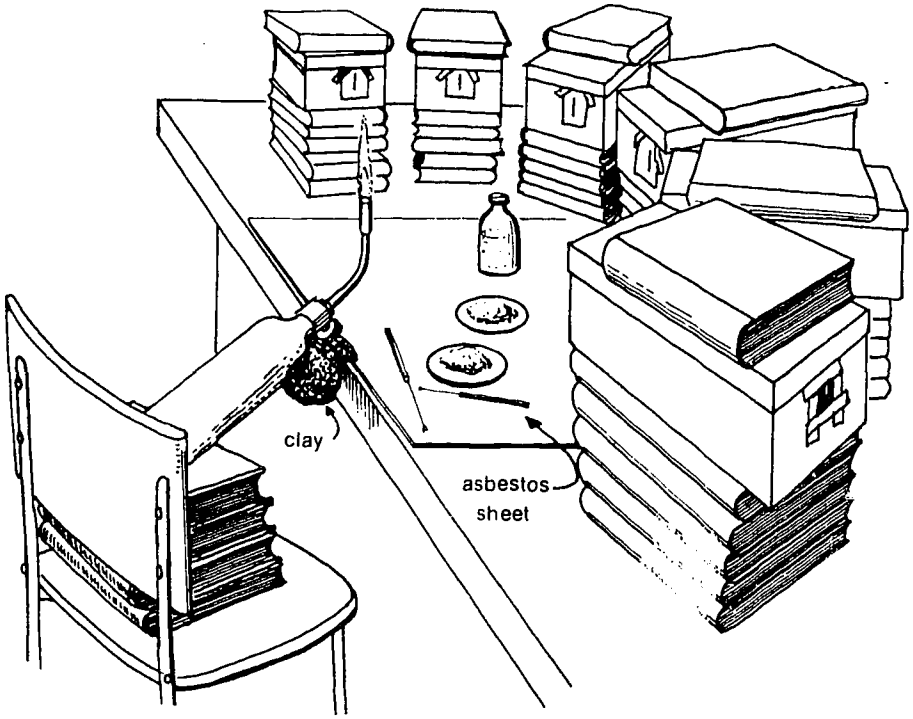



it upright against the taped blade, and tape another blade as closely to the strip as possible to make the opening between the blades narrow and parallel. Use care in handling the razor blades. Remove the strip of card and tape the entrance slit inside the box.

Paint the inside of the box flat black with tempera paint to cut down on reflections. Check your spectroscope by looking at a light bulb. Do you see a continuous spectrum? Notice where the spectrum occurs in relation to the entrance slit.

Now make several chemical holders for your spectroscope. First straighten a large paper clip. Twist one end into a circular loop using needle-nose pliers. Force the other end into a cork.

Set up several spectroscopes around a gas flame, as shown in the illustration below. Adjust them so that the light enters the vertical slits as you look through them.

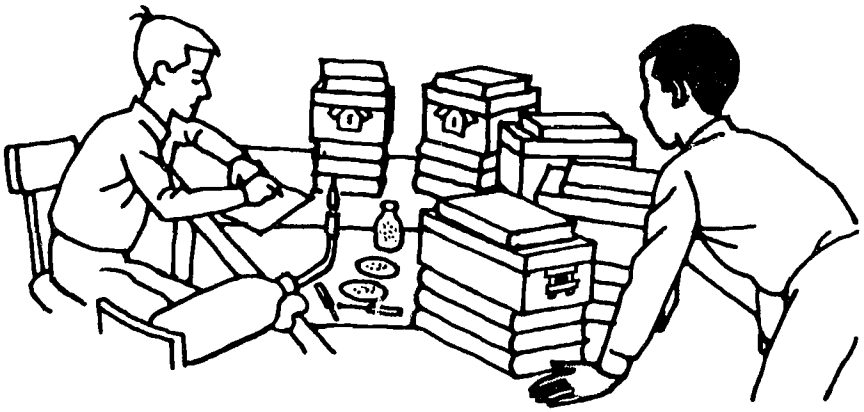



Vaporize some common salt in the flame. Dip the loop of the chemical holder into some water and then into some salt. A bit of salt will stick to the wire. Hold the loop in the flame while

someone carefully examines the spectrum of the vaporized salt. Do you see a continuous spectrum? How does the spectrum of a gas differ from that of a solid?

The spectrum you observe in the flame is called an *emission line spectrum*. The lines are really images of the slit. If you make the slit wider or narrower, the emission lines you see will be wider or narrower. If you replaced the smooth slit with a ragged one, each emission line would appear ragged. Because the slit is narrow, the light appears as a line. Scientists talk about spectrum *lines*. But, remember, the hot gas does not actually emit lines. It is just the design of the spectroscope that makes the light appear that way.

Observe the emission line spectra emitted by several different gases. Use the following chemical compounds if you can obtain them: calcium chloride, sodium bicarbonate, and lithium chloride. These compounds permit you to observe the spectra of calcium sodium, and lithium. The other components of each compound do not appear. Use a separate holder for each chemical. Hold the wire in the flame until it glows; then dip it in the chemical. Put the holder in the flame again while someone observes the spectrum through the spectroscope. Record the colors of the emission lines observed for each chemical.

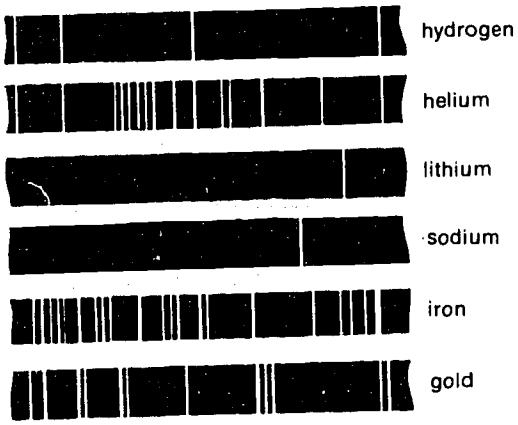


The pattern of emission lines of any element is unique—just as your fingerprints are unique. Nobody has fingerprints just like yours. No two elements have identical patterns of bright lines.

When you hold a substance in the flame of a gas burner, the substance heats up, melts, and then vaporizes. Atoms of the substance become a part of the hot gas of the flame. These atoms radiate light of certain wavelengths. The light goes out in all directions. A small part of the

light passes between the razor blades, through the grating, and into your eyes. It shows you the unique emission line spectrum of that kind of atom.

The special selection of wavelengths emitted by each gas is characteristic of that particular element. Scientists have vaporized many elements and photographed their spectra. The unique patterns of lines for these elements have been carefully charted. To find what elements a certain substance is made of, scientists need only to vaporize it and make it glow. Then by comparing its emission lines to those of known elements, they can identify all of the elements in the substance. Spectral fingerprinting is an important way to analyze materials on earth.



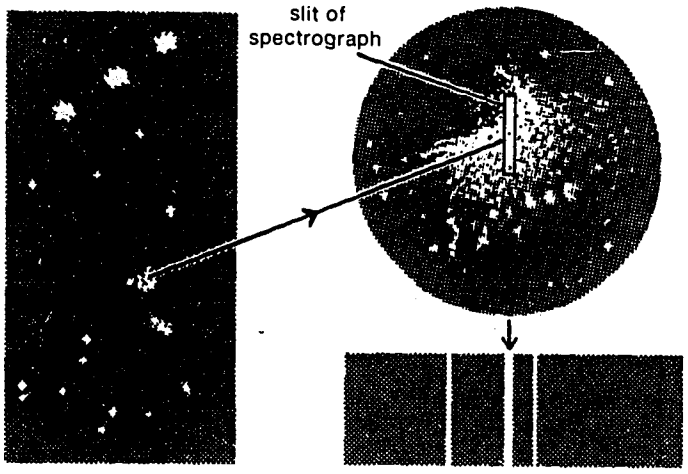

## ASTRONOMICAL EMISSION LINES

We cannot take a piece of the sun, or a comet, or Mars and vaporize it in our classroom to determine what elements are in each. Astronomers must get their information from the light these objects send out. They look for celestial objects that show emission lines. Then they can determine the elements in those objects.

In the winter constellation of Orion, the region near the middle star of Orion's sword is of special interest to astronomers. Photographs taken through telescopes show a bright, fuzzy patch surrounding a group of hot bluish stars. The patch is called the Orion Nebula (NEB-you-luh). The spectrum of the Orion Nebula contains a number of emission lines. Therefore, the nebula cannot be a solid: it must be a great cloud of

hot gas, emitting light. The lines in the spectrum show that the light is coming from atoms of hydrogen, oxygen, and several other elements. The gas is heated by the nearby hot blue stars.

There are many other bright, cloudlike regions, called nebulae (NEB-you-lee), visible in the sky. Their true nature baffled astronomers until a century ago when William Huggins of England examined them with a spectroscope. His discovery that the spectra of these nebulae had emission lines solved the problem of the nebulae.




There are many other objects in the sky that show emission spectra. The Northern Lights show emission lines of hydrogen, oxygen, and nitrogen. We know, therefore, that high in our atmosphere these kinds of atoms are radiating as a gas.

The spectra of most comets show emission lines, and so we know that at least part of a comet is gaseous. It is possible to identify the kinds of elements present in comets. The lines show the presence of carbon, nitrogen, carbon monoxide, and other molecules.

As meteroids enter the earth's atmosphere at high speeds, friction quickly heats and vaporizes them. They streak across the sky in a flash of light and are gone in a second or two. Astronomers have obtained a few spectra of meteors. Each spectrum shows emission lines.

In the spectra of meteors, the emission lines of iron, calcium, silicon, sodium, and other elements are found. The chemical elements making up these celestial visitors are the same elements we know on earth.

## ON YOUR OWN

Use the shoebox spectroscope to search for emission lines. Look at the spectra of fluorescent lights, mercury arc street lights, neon signs, and so on. Where do you find the strongest lines? Record your observations.

Spectroscopic analysis of glowing comets enables astronomers to determine their composition.
The heat of the sun vaporizes the outer layers of the solid head, and the gaseous tail streams out in the direction opposite the sun.

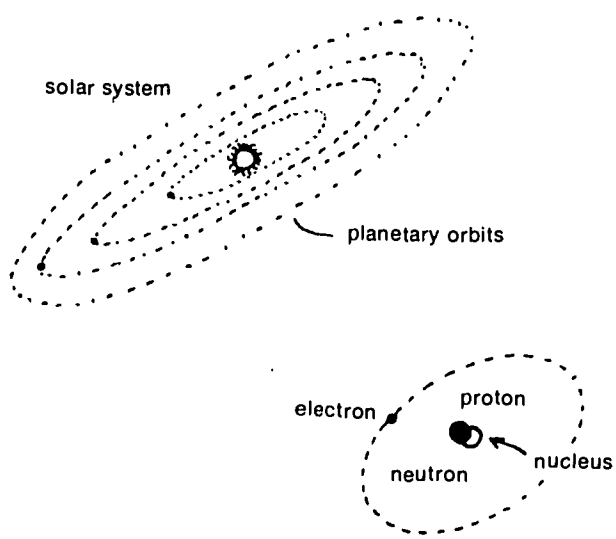
CHAPTER 8

# Atoms and Light

Solid hot objects radiate a continuous spectrum. Hot gases radiate at certain definite wavelengths only. Why are they so different? Indeed, why do hot things have spectra anyway? To find the answers to questions like these, we have to go to the heart of the matter—to the atom.

## AN ATOM MODEL

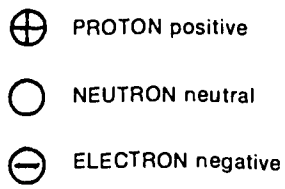
We have used two models previously to explain some of the behaviors of light—a wave model and a particle model. Now let us study an atom model that does a good job of explaining how atoms radiate light. This model was first conceived by the Danish physicist Niels Bohr (NEELS BORE) early in this century.




Imagine that an atom looks somewhat like the solar system. In the solar system the planets move in orbits about a central object—the sun. The atom model has two essential parts—a nucleus at the center and objects moving in orbits around the nucleus. In the model there are three basic particles: *protons*, *neutrons*, and *electrons*. The nucleus contains the protons and neutrons. The electrons move in orbits around the nucleus.

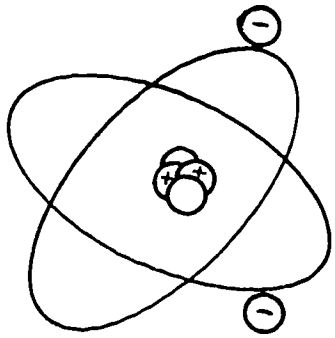
Nuclear forces are so strong that they keep the protons and neutrons packed together very tightly. The orbiting electrons are attracted to the nucleus by electrical forces.

Each proton carries a positive electric charge. The strength of this charge is always the same for every proton. A neutron is neutral; it has no electric charge. An electron carries a negative charge equal in strength to the positive charge of a proton. In any normal atom, there are as many negatively charged electrons in orbit as there are positively charged protons in the nucleus. There is no net charge. The atom is neutral.




You have found that no two elements radiate in the same wavelength pattern. Similarly, the atoms of each element are different from the atoms of every other element. A hydrogen atom is different from a helium atom and from every other kind of atom. Hydrogen atoms have the simplest nucleus of all—one proton. In orbit around the proton is one electron. The positive charge of the proton exactly balances the negative charge of the electron. If you had a balloon full of hydrogen gas, it wouldn't be charged at all.

Now put together an atom that isn't so simple. Combine two protons with two neutrons to make the nucleus. Two electrons are needed in orbits around the nucleus so that the atom will be neutral. The atom you have made is helium.

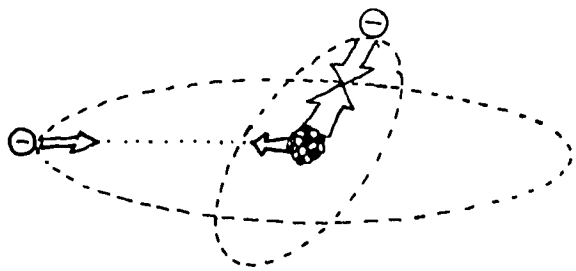


helium

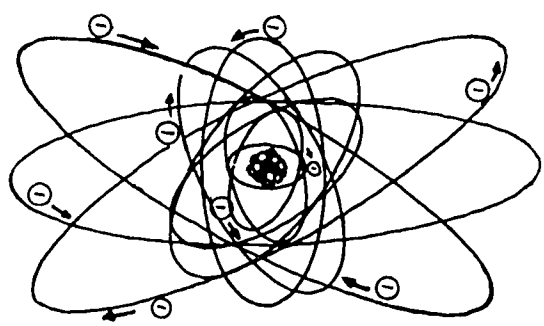
A neutral atom with three electrons in motion around the nucleus is called lithium. How many protons are in its nucleus? Most lithium atoms contain four neutrons in the nucleus, but some have only three. A lithium nucleus, therefore, contains a total of six or seven particles.

The nucleus of a neutral atom of gold has 197 particles, and 118 of these are neutrons. How many protons and electrons are there in the atom?

Like the solar system, a hydrogen atom is mostly empty space. How empty is that? Let a marble represent the nucleus of the hydrogen atom. On this scale the single electron would be the better part of a



mile away. In the real hydrogen atom, the electron is usually one-half an Angstrom away from the proton—only two-billionths of an inch. It is not surprising that you cannot see an atom.



The electrons moving about a nucleus are arranged in orderly orbits. Like the planets circling the sun, some electrons circle the nucleus at greater distances than other electrons. The electrical pull of the nucleus on close electrons is strong; its hold on more distant electrons is weaker.

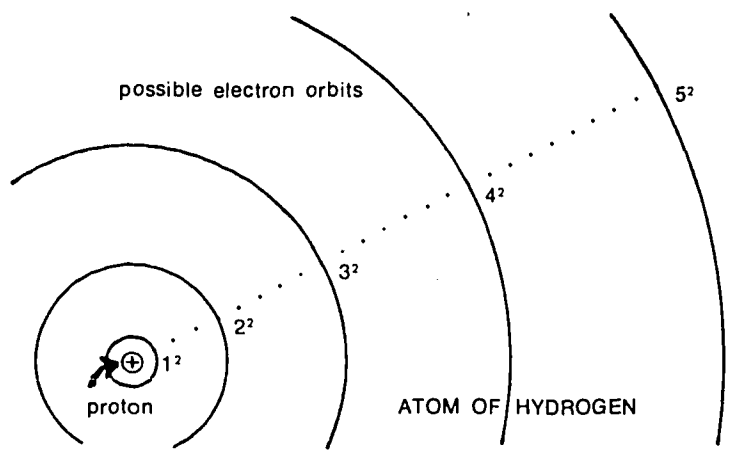
There are differences between the structure of an atom and that of the solar system. One difference is that the orbits of the planets are all nearly in the same plane, but the electron orbits in most atoms are not.

There is one major difference that is the key to how light is born in an atom. In the solar system a planet stays in the same orbit even after billions of years. But the electrons in an atom can jump into different orbits and then back again. In fact, they are doing so constantly in any gas that is emitting light.

## A HYDROGEN MODEL THAT RADIATES

Since hydrogen is the simplest of all atoms, let us concentrate on a model for hydrogen. The nucleus of the hydrogen atom has one proton, and, to complete the atom, one electron is in orbit about the nucleus. The smallest orbit that the electron can follow is a circle about half an Angstrom in radius. Call this path the innermost orbit. In only a millionth of a second the electron circles the nucleus billions of times. But it always stays in the innermost orbit unless the atom is disturbed in some way.

When the electron is moving in any orbit except the innermost, the atom is said to be *excited*. How does an atom get excited? Remember that the positive proton and the negative electron are pulling on each other. If an electron moves to a bigger orbit, it must somehow have been pushed or pulled outward. The electron must gain some energy if it is to move in a larger orbit.

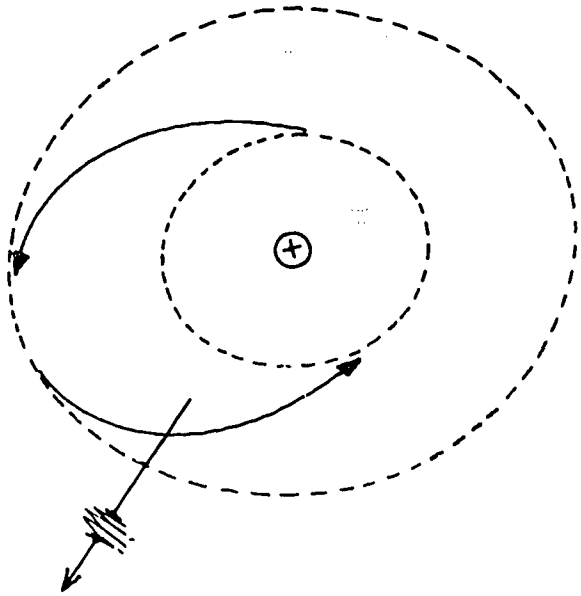



The nearest orbit the electron can jump to is four times as large as the innermost orbit. The next is nine times as large, the next is sixteen times, and so on. There is no end to the number of possible orbits. But notice that the spacings obey definite rules. There is no orbit that is 3.9

times as large as the innermost orbit or even 3.95; the second orbit is exactly 4 times as large as the smallest orbit. Since only orbits of a certain size are allowed according to the rules of the game, only an *exact* amount of energy can be gained by the electron as it moves out from one orbit to another.

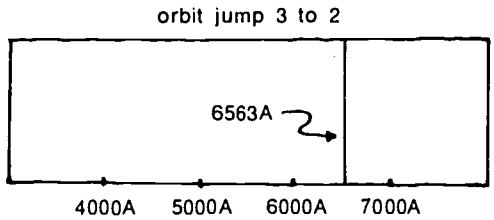
What happens after the electron gains or absorbs some energy and moves out to a bigger orbit? It immediately jumps back to the innermost orbit. It stays in the bigger orbit for only a small part of a millionth of a second.

What is the connection between emission lines and the electron jumps in an atom? Just this: When the electron moves from a bigger orbit to a smaller orbit, it loses the energy it had gained. This energy is released as a single bundle of energy—as a tiny burst of light. The little bundle of light leaves the scene at the same time the electron is jumping inward toward the smallest orbit. The bundle of light the atom radiates is also a bundle of energy. The bundle acts like a particle and is called a *photon* (FOE-tahn). A photon is a small particle of light or energy.

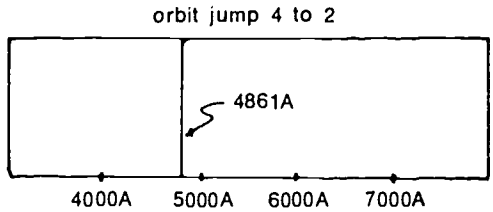


When we picture Bohr's model of the atom, we are doing a sort of about-face. Previously we have emphasized the wave model of light. To account for the interference of light going through two pinholes, the wave model worked better. But to explain the radiation of light with the Bohr model, the particle model of light works better. We think of photons as moving particles of light.

If light is photons streaking out of atoms, what is the meaning of wavelength in the Bohr model? Each time the electron in our hydrogen atom jumps inward from the third orbit to the second orbit, a photon is emitted. The spectroscope would detect these photons as red light with a wavelength of 6563 Angstroms. This wavelength is in the red part of the spectrum. Many such photons are emitted in all directions by hot hydrogen. If enough struck your eyes each second, you would see red light. In a spectroscope you would see the red spectrum line of hydrogen.



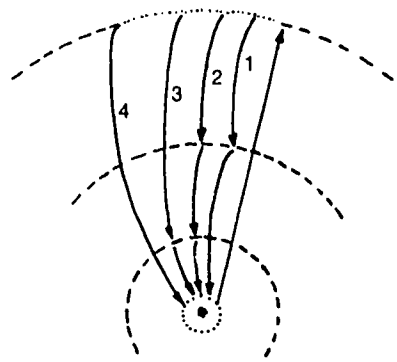

Remember that the wave model and the particle model are only convenient ways to think about some of the behaviors of light. Some of the things light does are the same things we observe waves to do; other behaviors of light are more like the behaviors of particles. But neither the wave model alone nor the particle model alone can tell the whole story. Therefore, to save words, we will speak of photons as if they had wavelengths.



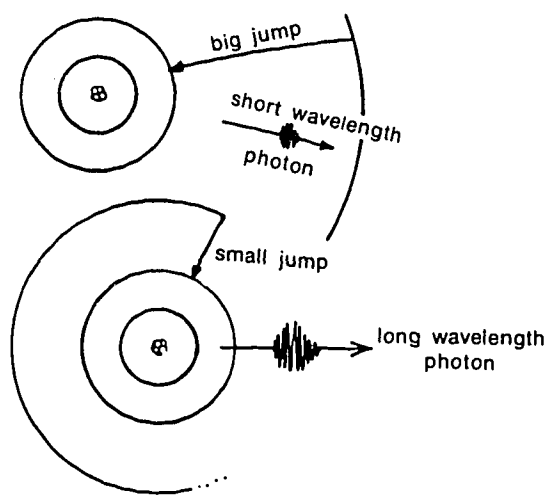

Hydrogen emits photons of other wavelengths, too. When an electron jumps from the fourth orbit straight down to the second orbit, out goes a photon of wavelength 4861 A in the blue-green part of the spectrum.

There are a number of ways the electron can return to the innermost orbit. Think of an electron that has just gained enough energy to move out to the fourth orbit. There are four ways for the electron to go from

the fourth orbit to the first. There is only one way to go from the second to the first orbit. How many ways from the fifth to the first?




If the electron goes from the fourth orbit to the innermost orbit in one jump, it will emit a photon of energy. If it stops momentarily at both the third and second orbits, it will emit three photons of light. The sum total of the energy of these three photons will be exactly the same as the energy in the one photon emitted by a four-to-one jump.

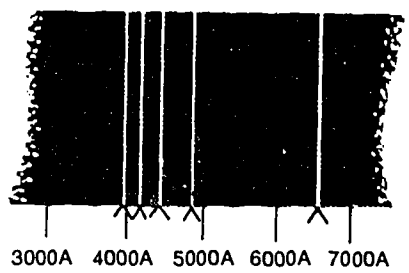



The wavelengths of the photons emitted by a hydrogen atom depend on the energy of the photons. A high-energy photon has a short wavelength. A low-energy proton has a long wavelength. In the hydrogen atom we have seen that there are only certain permissible orbits. To move from one of these orbits to another, only a certain definite amount

of energy is involved. That is why only certain definite wavelengths are emitted by the hydrogen atom. A hydrogen atom cannot emit yellow light because it has no pair of orbits with the correct energy separation.

Here are some electron jumps and wavelengths emitted by the hydrogen atom:

| *Wavelength* | *Color* | *Electron Jumps* |
|---|---|---|
| ..... | no photon | 2 to 2 |
| 6563 A | red | 3 to 2 |
| 4861 A | green | 4 to 2 |
| 4340 A | blue | 5 to 2 |
| 4102 A | violet | 6 to 2 |
| 3970 A | ? | 7 to 2 |




Bohr's model of the hydrogen atom is very useful. It predicts the wavelengths that hydrogen emits, and these wavelengths are exactly those observed in the spectra of hydrogen. Thus Bohr's model is used frequently by scientists.

## EXCITEMENT

How do we get the atoms of a gas excited in the first place? How do we give the atoms energy so that the electrons can move to outer orbits?

You have probably seen an experiment in which a balloon is put in a refrigerator. After a short time the balloon shrinks in the cold. What happens? The balloon is kept inflated by the continual push of molecules against the inside surface of the balloon. The molecules are always in motion, and their constant banging against the inside keeps the balloon pressed outward.

The speed of the molecules depends on the temperature of the gas. When you talk about the temperature of a gas, you are really talking about the speed at which the molecules of the gas are moving. The particles are in rapid motion. They hit each other as well as the walls of the container. In a refrigerator the gas is cooler and the molecules are not in such rapid motion. Hence the balloon shrinks. If we were to heat the balloon, the molecules would move faster. Each one would hit the inside surface harder and more often. The balloon would expand.

Imagine heating hydrogen in a balloon to a high temperature. The atoms move about even faster. They hit the inner surface of the balloon and also each other, harder and harder. In one of these collisions an electron of one of the atoms may be bumped outward to a bigger orbit. The energy the electron needs to move to this larger orbit is obtained from the motion energy of the other atom. The harder or more energetic the collision, the farther out the electron can move. The collision is needed so that the energy of motion of one atom can be transferred to the electron of the other atom. This is one way of exciting an atom—by collision with another atom. It is called *collisional excitation.*

A hot mass of gas consists of countless numbers of atoms. At any instant there are umpteen atoms that have just been excited and now have electrons jumping from outer orbits to inner ones. Photons are speeding out from these jumps in all directions.

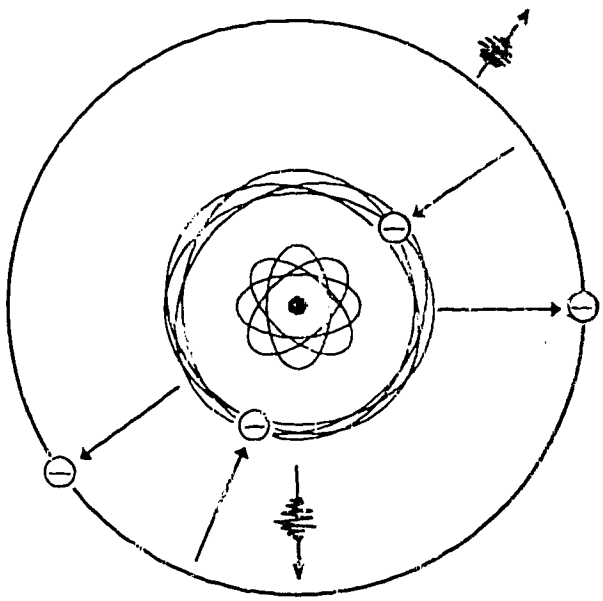
Perhaps now you can see why it is necessary to heat a gas before it can emit light. Ordinarily, in gases such as in the atmosphere in a room, the collisions are not energetic enough to excite the atoms. If the electrons always stay in their innermost orbits, the atom cannot emit. The atoms of the room's atmosphere do not emit light because the electrons in the atoms are all in their innermost orbits.

## OTHER ATOMS

The Bohr model of the atom works very well for hydrogen. But what about other elements? Their atoms have more electrons than hydrogen does, and the electrons move in a greater variety of orbits. The picture is more complicated.

In complicated atoms the electrons in the far-out orbits must be attracted very feebly compared with those occupying orbits close to the nucleus. It is these outer electrons that change orbits to produce the

spectrum. These outer electrons have their own innermost orbits. There are other electrons in orbits closer to the nucleus, but the outer electrons cannot get into these orbits. When two atoms collide, the outermost, loosely held electrons are the ones that get bumped out to even bigger orbits. The atoms radiate light when these electrons jump back in to their own smallest orbits.



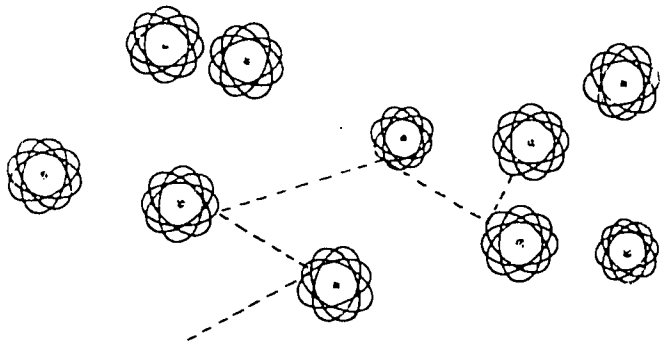
Outer electrons make jumps in outer orbits only.

Now you can see why each gas has a distinctive spectrum. The outermost electrons in a sodium atom occupy orbits quite different from those belonging to a calcium atom. Thus the spectrum of sodium differs from that of calcium. Different wavelengths of light escape when the outermost electrons in different elements jump inward. Each element has its own unique pattern of spectral lines.

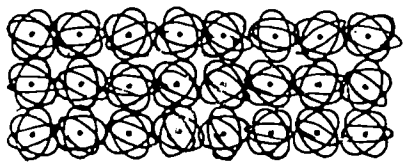
The more you heat a gas, the faster its atoms fly about, and the more vigorously they collide with each other. More atoms collide hard enough so that electrons are jolted to outer orbits. The hotter the gas, the greater are the number of excited atoms. The gas glows more brightly because more atoms have an electron that is jumping back into a smaller orbit. But the wavelengths of the photons emitted by the atoms are just the same as they are when the gas is cooler. The pattern of possible lines is always the same, wherever and whenever a particular gas is radiating.

## CONTINUOUS SPECTRA AGAIN

Now you have a model of an atom that can radiate. So far, this model applies only to atoms in a gas. You know that solid bodies are made of atoms also. Why does a solid give a continuous spectrum while a gas gives only lines? Do we have to abandon our model to explain the spectra of solids?



To understand the answer, we must compare the separation of atoms in a gas and in a solid. In a gas the atoms fly about and sometimes collide. During the atom's flight its neighbors have no influence on it. Most of the time it moves in free flight—as though no other atoms were around. Only a small part of the atom's life is spent in collision with other atoms.



An atom in a solid body, however, leads a much different kind of life. It is never free of closely packed neighbors as they press against it from every side. The outermost electrons of an atom in a solid are almost as close to the nuclei of several neighboring atoms as they are to the nucleus of their own atom.

What happens as a consequence of this crowded condition? An outermost electron is pulled by the electrical forces of these neighboring atoms as well as by its own nucleus. So the orbit separations which determine how the electron can jump can no longer follow definite laws.

With no definite orbits, an atom is no longer confined to radiating a definite set of wavelengths. It can radiate any one of a variety of wavelengths because a variety of orbits is possible. At any given

moment, the billions of atoms in a solid are emitting billions of different wavelengths. Hence the solid body radiates a continuous spectrum.

## A CONTINUOUS SPECTRUM FROM GAS

Is it possible for a gas to radiate a continuous spectrum as a hot solid does? In a rarefied gas, as we have seen, the atoms are far enough apart so that an outermost electron of one of them owes its electrical allegiance to its own atom almost all the time. But think of compressing this gas into a much smaller volume. The atoms move about in a smaller space; the gas is denser than before. An outermost electron feels constantly changing pulls as neighboring atoms continually pass near it. The orbits of the harassed electrons are continually being altered be-

gas at low pressure  gas at high pressure

cause of passing neighbors. Thus the electrons can make jumps that are bigger or smaller than usual. They emit photons of many different wavelengths. This variety of wavelengths means a color spread rather than a neat emission line of one sharp wavelength. The more a gas is compressed, the more the atoms disturb one another. The compressed gas begins to radiate a continuous spectrum just as a glowing solid does.

Let us summarize the ways that light and radiating bodies behave. First, a hot gas radiates an emission line spectrum when the pressure is very low. Second, if a hot gas is compressed, it radiates a continuous spectrum. A solid radiates a continuous spectrum also. These rules about radiation were first formulated by the physicist Robert Kirchhoff (KIRK-hoff) in the nineteenth century.

## STARS AND THE CONTINUOUS SPECTRUM

We have already used the continuous spectrum to find the temperatures of stars. Now we see that the continuous spectrum contains another clue about the radiating stellar material: a star must be either a hot solid or a hot compressed gas. Even as recently as the beginning of this century, astronomers were still not sure which was the case. Today, however, all

astronomers agree that the continous spectrum of the stars comes from compressed gas. The stars are simply too hot to be solid bodies.

Our understanding of the way materials radiate enables us to read more of the message of starlight. Now we can see that it is possible for the sun, or any star, to be entirely gaseous and yet radiate a continuous spectrum.

## ON YOUR OWN

Scientists use certain symbols to describe the number of particles in an atom. For example, $_2He^4$ represents an atom of helium.

The subscript is called the *atomic number*. It shows how many protons are in the nucleus.

The superscript shows the sum of neutrons plus protons in the nucleus.

$_2He^4$

The letters are the symbol for the element.

This system is called *atomic notation*. Now, copy the following table and fill in the blank spaces.

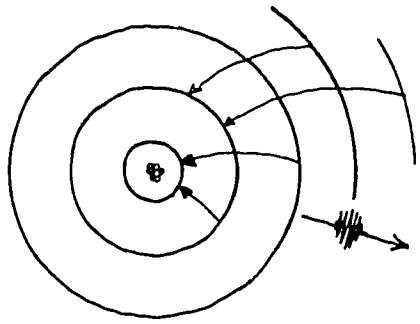
| *Element* | Litnium (Li) | Oxygen (O) | Sulfur (S) | Chromium (Cr) | Zinc (Zn) | Lead (Pb) |
|---|---|---|---|---|---|---|
| *Protons* | 3 | 8 | | 24 | | |
| *Neutrons* | 4 | 8 | 16 | | | 125 |
| *Electrons* | 3 | | | | | |
| *Atomic Number* | 3 | | | | | |
| *Protons + Neutrons* | 7 | | 32 | 52 | | 207 |
| *Atomic Notation* | | | | | $_{30}Zn^{65}$ | |

CHAPTER 9

# Stars and Stripes

The Bohr model helps you to understand how atoms of hot gases give off light. When the atoms are packed closely together, they radiate only certain wavelengths. An emission line spectrum is seen. You can identify the elements in the gas from the bright-line pattern in the spectrum.

spectral fingerprint



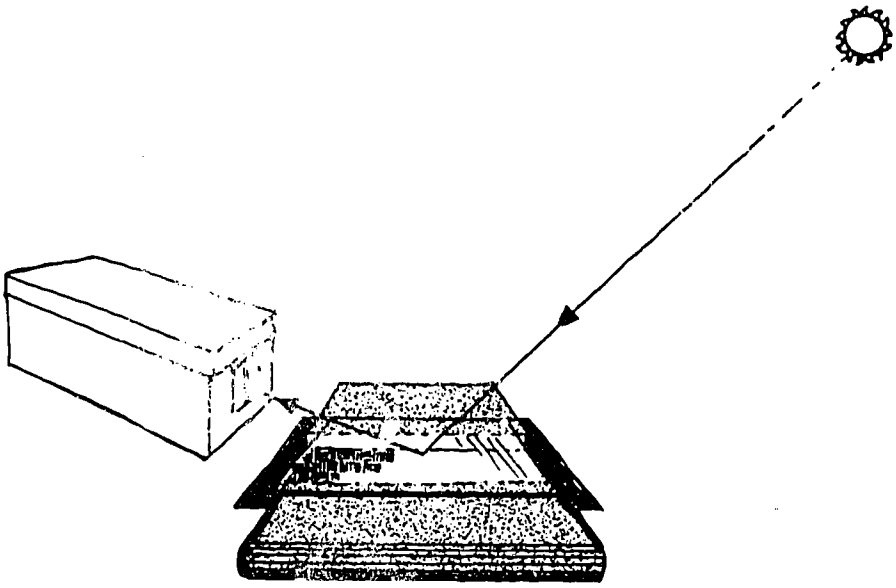
In a star in which the atoms of the gas are pressed close together, no emission lines are seen. The star spectrum resembles that of a glowing solid—a continuous spectrum. It has all the colors—like a rainbow. If an astronomer is to identify the elements of which a star is made, he must search for other clues in the message of starlight. Let's start by examining the spectrum of our nearest star—the sun.

## THE SUN'S SPECTRUM

Place an 8 × 10-inch pane of glass on two books. Lay a sheet of black construction paper under the glass to absorb some of the

glare of light. Position the equipment to reflect the image of the sun as it comes through the classroom window glass. The purpose of this arrangement is to reduce the light from the sun, which is much too bright to be observed directly. Now tape a piece of smooth wax paper over the slit of your shoebox spectroscope to act as a filter. After this filter is in place, you can point your spectroscope at the sun's image reflected by the glass. You now can observe the sun's spectrum.

You will see many dark horizontal lines crossing the spectrum. These are caused by tiny nicks on the edges of the razor blades. Try to ignore these lines. Look in the area where blue and green merge. Do you see thin, vertical dark line? Look for other vertical dark lines. There is one in the yellow-orange part of the solar spectrum. You should see several others.

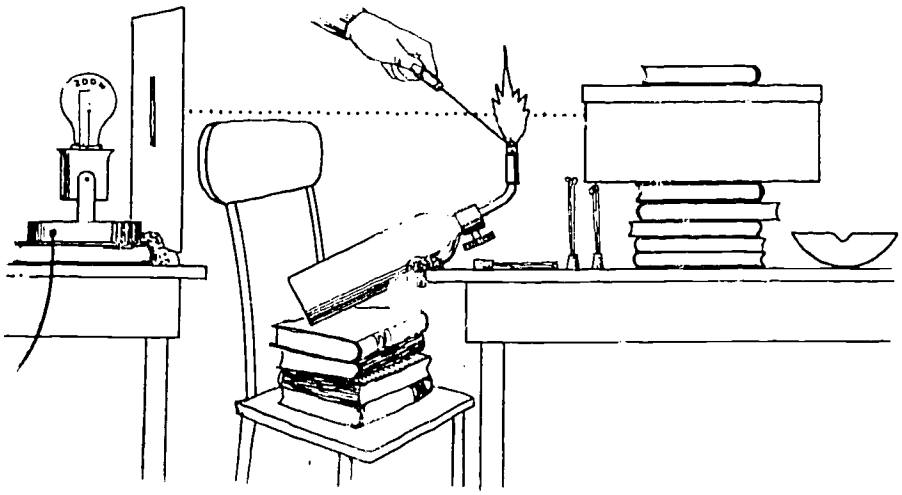


The spectrum of the sun is continuous, but it also has numerous narrow dark lines superimposed on the continuous background. As far back as 1802, William Wollaston saw a few dark lines in the solar spectrum. Not many years later and with better instruments, Joseph von Fraunhofer (FROWN-hoe-fer) observed several hundred dark lines. He did not know what they meant, but he did map their positions in the solar spectrum. Because of his pioneering studies, the more prominent features in the sun's spectrum are called *Fraunhofer lines.*

What do these lines mean? Do their positions in the solar spectrum offer any clues as to their origin? Think of the dark line in the yellow-orange part of the spectrum. Can we determine its origin?

## DARK LINES FROM A GAS

Set up a shoebox spectroscope to examine salt—sodium chloride—in the flame of a gas burner. For this activity, arrange a 200-watt bulb about two feet behind the flame. Make a slit in a cardboard shield and place the shield in front of the bulb. This activity will not work unless the bulb, flame, and spectroscope are in a straight line. Construct a wire holder like those used in previous activities, but make three wire loops so that more salt can be held and vaporized.

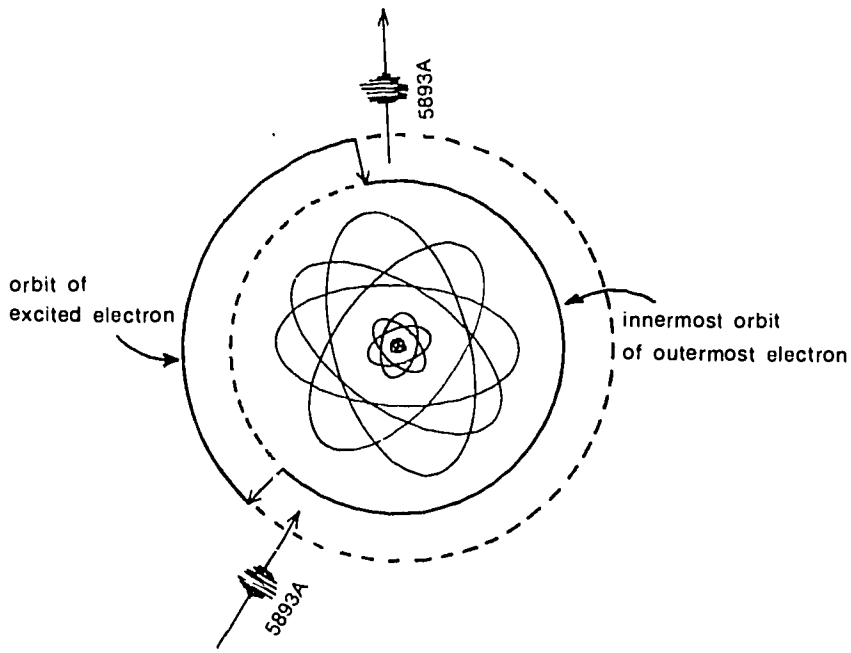



Darken the room. Have a classmate dip the wires into water and then into the salt. Have him hold the wires in the flame while you peer through the spectroscope. The yellow emission line of hot sodium atoms will be seen. Now turn on the light and heat more salt in the flame. What do you see where the emission line of sodium crosses the continuous spectrum of the bulb?

By looking carefully, you can see a thin dark line crossing the continuous spectrum from the bulb. This dark line is exactly where the sodium emission line appeared. When the sodium is gone, the dark line

is gone. Somehow the gaseous sodium from the salt must have produced the dark line. Can our model of the atom explain what you have just seen?

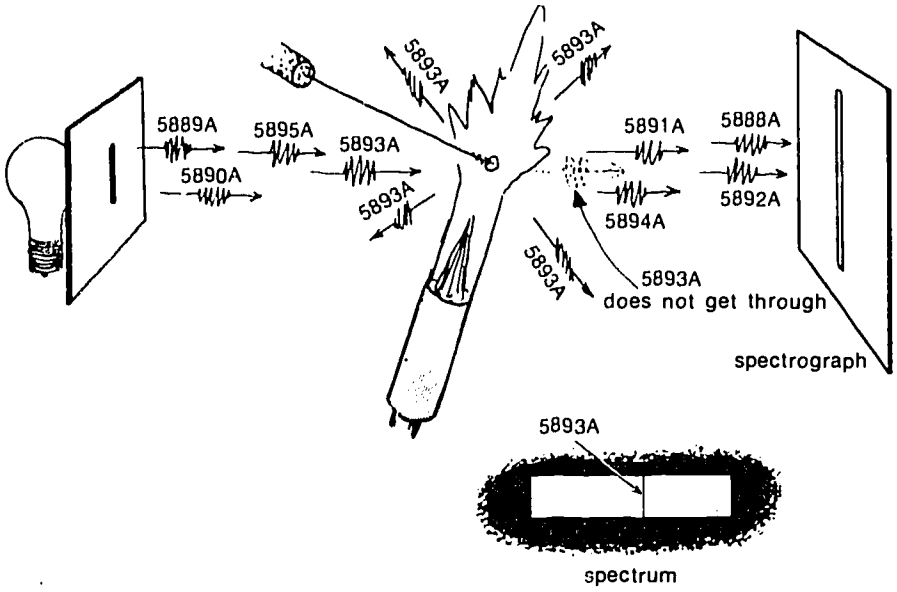
When sodium chloride is placed in a flame, it vaporizes. Individual atoms of sodium are released from the salt and fly about at high speeds. Some of these atoms collide with other atoms. The electrons of these atoms absorb energy of motion during the collisions and jump to a higher orbit. As the electrons return to their innermost orbits, they release their excess energy, and photons of certain wavelengths are emitted. That is the origin of the yellow sodium line.




Remember that only certain orbits are possible in a rarefied gas. The sodium atom emits a yellow light of wavelength 5893 A when the outermost electron jumps from its smallest excited orbit down to the innermost orbit that it can occupy. The amount of energy contained in a photon of wavelength 5893 A is an exact quantity. It is different from the amount of energy contained in a photon of any other wavelength.

At any time in the sodium gas, there are excited atoms and unexcited atoms. The light from the light bulb shines through this cloud of sodium atoms before it reaches the spectroscope. Billions of photons of all different wavelengths stream into the cloud of sodium vapor.

Let us follow a 5893 A photon on its way from the light-bulb filament to the spectroscope. The photon proceeds along nicely until it enters the cloud of sodium gas. If our 5893 A photon encounters an unexcited sodium atom, something happens. The sodium atom can use the energy of the 5893 A photon to move its electron from orbit one to orbit two. The 5893 A photon has just the right amount of energy to do so. So the sodium atom *absorbs* the 5893 A photon, and the electron moves to orbit number two. The energy of the photon has been used to move the electron. An atom can become excited by absorbing a photon of just the right energy. The 5893 A photon no longer exists. It has disappeared. It never completes the journey to the spectroscope.



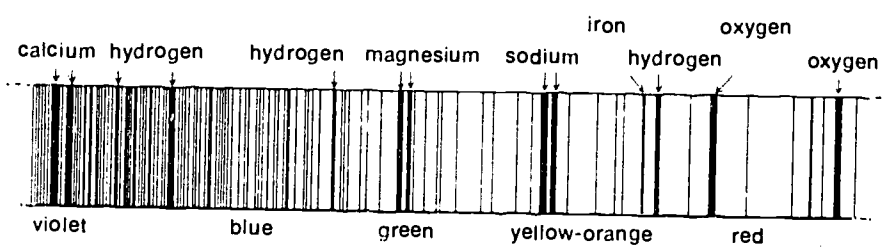

In the gas, there are enough sodium atoms to absorb almost all the 5893 A photons that try to pass through. Very few of these photons get through the cloud without meeting a sodium atom. The sodium atoms are unaffected by 5890 A photons, or 5891 A photons, or even 5892 A photons, or practically any other wavelength in the visual region. These other photons pass right through the gas and reach the spectroscope, producing the continuous spectrum that you see. There is a dark space where the 5893 A photons belong, because these photons were absorbed by the sodium gas. You see a dark line in the spectrum, an *absorption line*.

What happens to the sodium atom that has been excited by the photon absorption? You may remember that an excited atom immediately becomes unexcited by emitting a photon of light – a brand new 5893 A photon. The original 5893 A photon was headed directly for the spectroscope slit before it was absorbed by a sodium atom. The brand-new 5893 A photon can be re-emitted in any direction. Very rarely will it be emitted in the same direction the original photon was traveling. So only very few of these new photons enter the spectroscope slit.

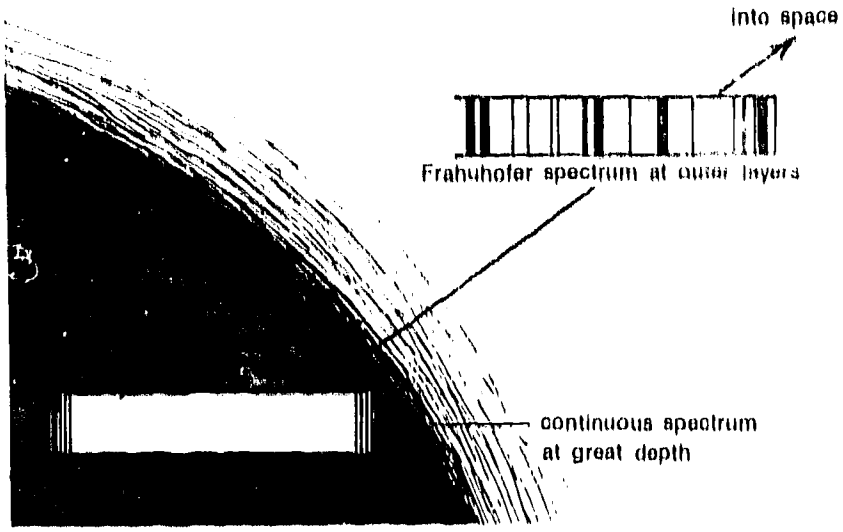
Here is another generalization about spectra, also discovered by Robert Kirchhoff. You can see a dark-line spectrum when there is a gas between your spectroscope and the source of a continuous spectrum—provided the gas is not as hot as the background light source. The dark-line pattern is the same as the one the element can emit.

## BACK TO THE SUN

You have observed that the spectrum of the sun has many dark lines. Can you now think what causes them? The sun's continuous spectrum originates at depths where the solar gas is rather compressed, so the spectrum from these hot zones is continuous. Higher, in the outermost layers of the solar gas, the pressure is lower and the atoms are not so crowded. Here the gas is thinner and cooler, just as it is at great heights in our own atmosphere. These layers of solar atmosphere are the last barrier the continuous radiation must pass through in making its escape into space. The atoms in the solar atmosphere absorb their characteristic wavelengths as the radiation from below passes through. The result is the dark-line spectrum of sunlight.

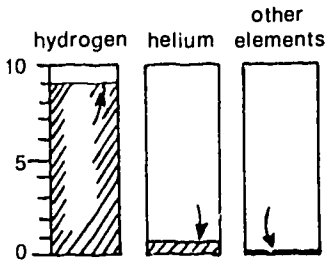



The diagram above shows some of the darkest Fraunhofer lines in the spectrum of the sun. These absorption lines identify the presence of an element just as surely as emission lines do.




Using the same method as before, observe the solar spectrum again. Be sure the wax paper filter is in place. Carefully examine the absorption lines in the spectrum of the sun. Which elements can you identify in the atmosphere of the sun?

By carefully studying the many thousands of absorption lines, astronomers can identify the kinds of atoms present in the sun. What do they find? First, every element found in the sun is also known here on the earth. Second, more than 60 of the 103 known elements have been identified in the spectrum of the sun. Probably the sun contains every kind of element, but some, like radium [illegible] uranium, must be uncommon since we do not detect any of the [illegible] lines.




About nine atoms out of ten in the sun are hydrogen. Most of the rest are helium. One atom out of every thousand is something other than hydrogen or helium. Leading the pack among these heavier atoms is oxygen, followed by carbon, nitrogen, and neon.

## OUTWARD TO THE STARS

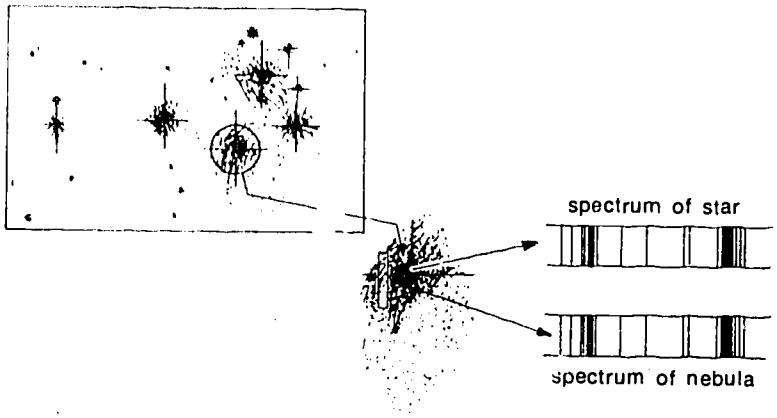
Almost everywhere in the sky, the stars show the same kind of spectrum – absorption lines slicing across a bright continuous spectrum. So almost all stars are built on a common pattern – a compressed gas emitting a continuous spectrum and a gaseous atmosphere that absorbs certain wavelengths as the radiation passes through. The elements we find in one star are also present in another. Hydrogen is always the most abundant, with helium following.

Some stars are hot; some are relatively cool. Some stars are very bright; others are dim. Some are large; others are small. From the dark lines in their absorption spectra, we know that they are all built of the same kinds of atoms and that they all possess rarefied atmospheres above a denser gas.

## ON REFLECTION

You have watched dust floating in the light beam of a projector. How did you "see" the dust? Light from the beam was reflected in all directions by the irregular-shaped dust particles. Some of the reflected light entered your eyes.

You have looked at the spectrum of the sun by aiming your spectroscope at a reflected splotch of sunlight. The absorption lines were faithfully reproduced.

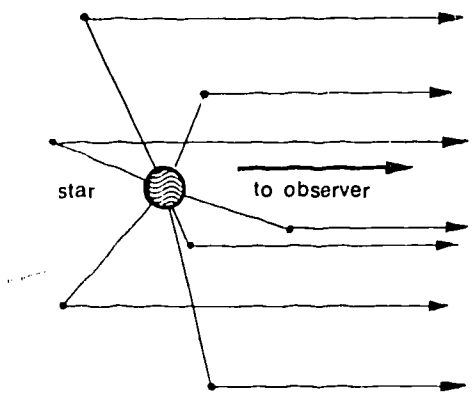



You can see the moon on a clear night because sunlight strikes its surface and is reflected to your eyes. If you examined sunlight reflected from the moon, you would see the same lines you saw before. The spectrum of the moon is a carbon copy of the sun's spectrum. So, too,

is the spectrum of the innermost planet, Mercury. From moon and Mercury you get a spectrum of the sun. The illuminated chalk dust would give the spectrum of the projector bulb.

Some night, look for the Pleiades (PLEA-uh-deez) in the autumn or winter sky. This little cluster of stars is sometimes called the Seven Sisters, although most people can manage to see only six stars in it. A telescopic photograph of the Pleiades shows that these stars are surrounded by a faintly luminous cloud—a nebula. Is this nebula a cloud of gas like the Orion Nebula? Does its spectrum show emission lines? How do astronomers find out?

Photographs of the spectrum of stars in the Pleiades show the usual continuous spectrum with dark lines. Photographs of the spectrum of a little patch of nebula near one of the stars show a carbon copy of the absorption spectrum of the star. There are no emission lines as in the Orion Nebula. The spectrum lines are dark, not bright. The spectrum shows that the nebula cannot be a radiating gas.




The spectrum shows that in the space surrounding these stars there are small grains of solid matter. Astronomers call these particles *interstellar dust*. Not much is known about the size or composition of these dust particles. However, they do reflect light from the star they are near. So the spectrum of this nebula is the same as the starlight.

## PLANET EARTH

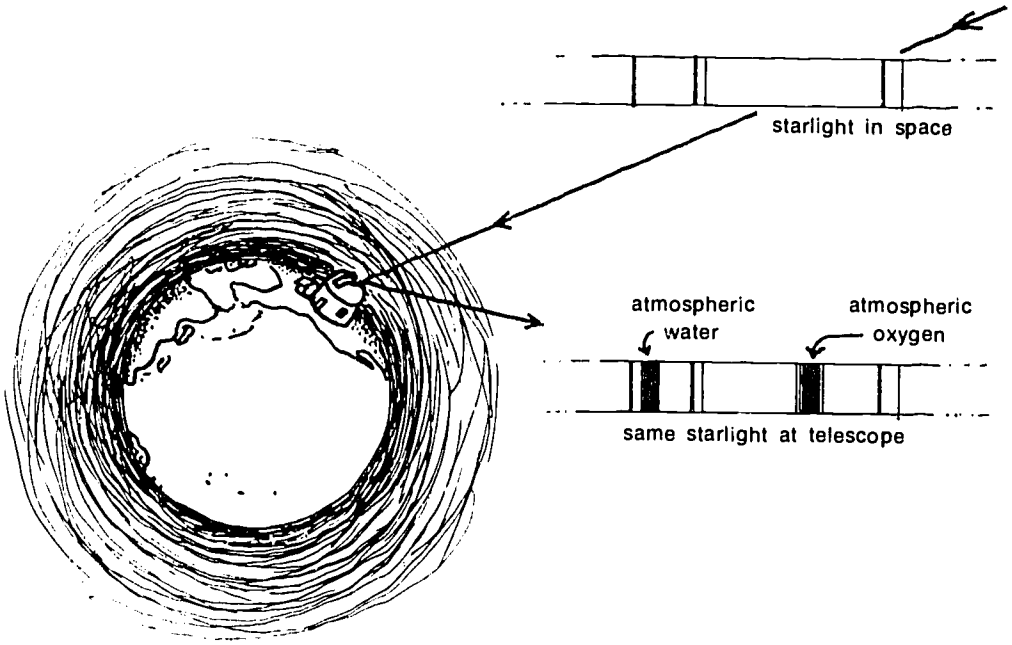
Surrounding the earth is an ocean of air. Our atmosphere is a gas consisting mostly of nitrogen and oxygen. It also contains water vapor and a number of other gases. Whenever we observe light from the moon, or

from a nebula, or from a star, the light must pass through this atmospheric ocean to reach our eyes.

What would you expect to happen to the light during its journey through the air? You know that the rarefied atmospheres of stars absorb outbound photons and cause dark lines. What of the elements in the earth's atmosphere?

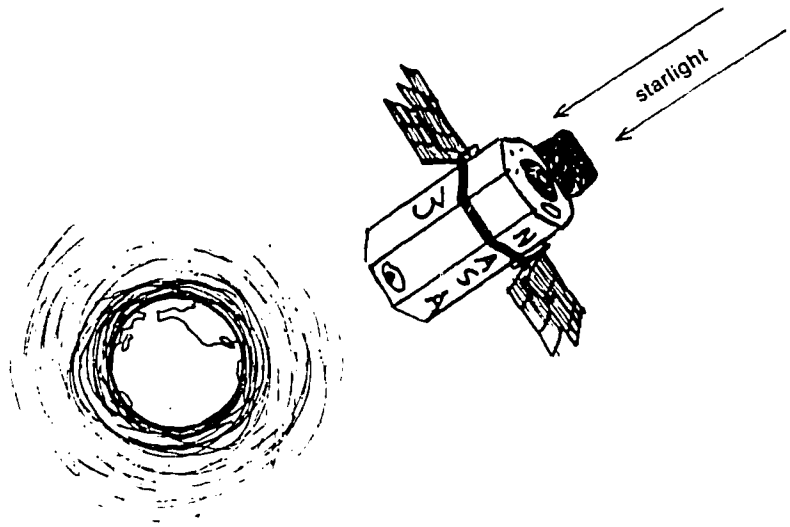
Look back at the diagram of the solar spectrum on page 91. In the red portion you see two heavy lines identified as oxygen. These lines are caused by oxygen molecules in our atmosphere. Our air is cool enough so that oxygen atoms stick together in pairs, forming molecules.

The spectrum of oxygen molecules is entirely different from that of oxygen atoms. We know that the oxygen molecules we observe must be in the earth's atmosphere. They could not be in the sun; it is far too hot for such pairs to link together there.




Water molecules, carbon dioxide molecules, and other molecules also form lines in the spectrum, mostly in the infrared or in the ultraviolet. Because the atmosphere absorbs radiation of many wavelengths, only a small part of the infrared and ultraviolet radiation from the stars can get through the earth's atmosphere. The radiation is absorbed before it can reach the ground. If your eyes were sensitive only to the

ultraviolet and infrared parts of the electromagnetic spectrum, you wouldn't see much if you looked at the sky. To read the ultraviolet and much of the infrared, you would have to board a spacecraft and get above most of the atmosphere of our planet. The wavelengths most successful at getting through to us on the ground are those in the visible and radio regions of the electromagnetic spectrum.



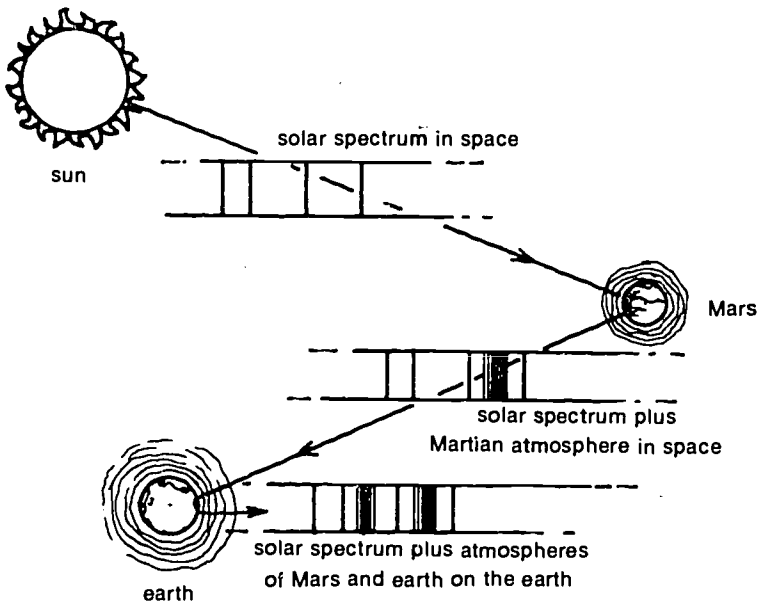

## DENIZENS OF THE SOLAR SYSTEM

You have learned something about the sun from its spectrum of dark lines. You also know that the earth's atmosphere puts its own imprint on the spectra of sun and stars. These absorption lines tell us something about the composition of our atmosphere. Since the moon and Mercury duplicate the spectrum of the sun, we can conclude that these bodies do not have atmospheres. If they did, we would observe extra absorption lines in their spectra.

How about the other planets? When we look at the spectrum of Mars, for example, we find something new. Sunlight goes to Mars, reflects from the Martian surface, and comes to our spectroscope through the earth's atmosphere. We see absorption lines from the atmospheres of the sun and the earth, and some additional lines formed in the Martian atmosphere. These lines reveal that Mars has a very thin atmosphere containing carbon dioxide molecules and water molecules.

Jupiter, the giant planet, has been found to contain large amounts of ammonia gas and methane marsh gas. All the planets except Mercury and Pluto have atmosphere of one kind or another.

The distinctive pattern of absorption and emission by each element has proved to be a powerful tool in analyzing starlight. A star appears as no more than a point of light through even the most powerful earthly telescope. Yet its spectrum reveals the elements of which it is composed and the plan of the star's construction: a compressed gas surrounded by a low-pressure atmosphere. Atmospheres of objects that men have never visited can be analyzed. It is safe to say that without a knowledge of spectra and the way they originate, astronomy as a science would have progressed little since the days of Kepler and Newton.

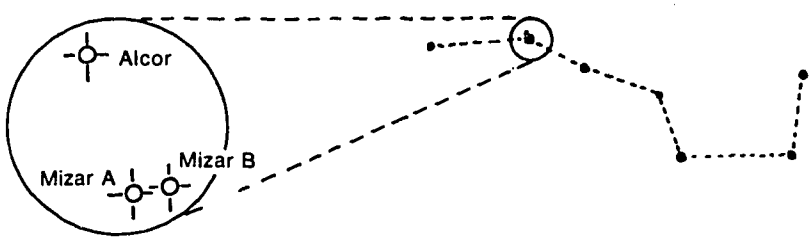


CHAPTER 10

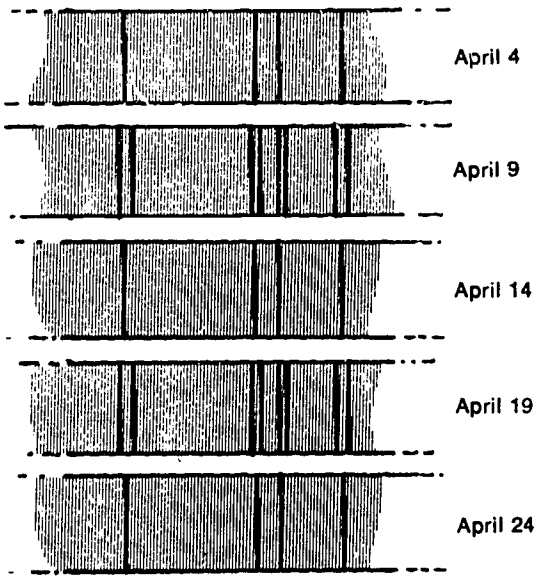
# To and Fro

## THE PUZZLE OF MIZAR

At the bend of the Big Dipper's handle lies the star Mizar. On a clear night a fainter star can be seen next to Mizar. This star, Alcor (al-CORE), is actually a great distance from Mizar, but from the earth it appears only one-fifth of a degree away.




In 1650, the Italian astronomer Giovanni Riccioli (jo-VAH-nee rich-ee-OH-lee) discovered that Mizar had an even closer companion. Faint Mizar B slowly revolves around the much brighter Mizar A, taking several thousand years to complete an orbit.



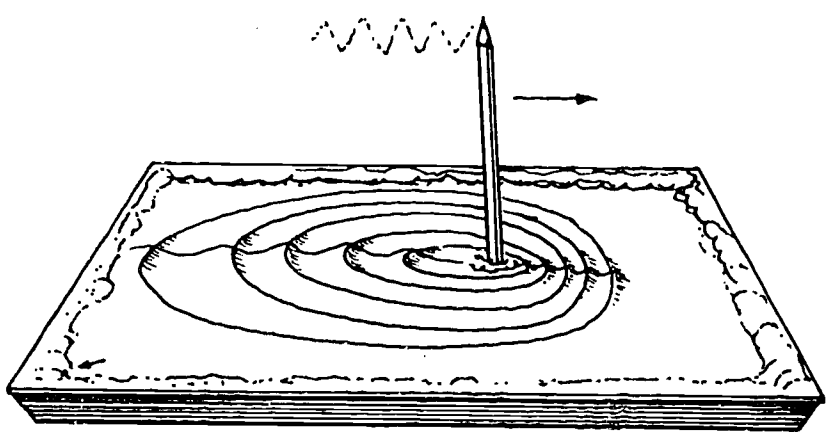
More than two centuries later, in 1889, E. C. Pickering at the Harvard Observatory studied the spectrum of Mizar A, the brighter star of this close pair. Pickering found a curious thing. At one time the spectrum of Mizar A looked like that of an ordinary white star, with a temperature of about 10,000° K. A few days later, however, the spectrum showed that all the dark lines were double and shifted from their normal position. Further studies showed that the spectral lines of Mizar A did not shift on just one occasion, but did so regularly.

## DOPPLER CHANGES

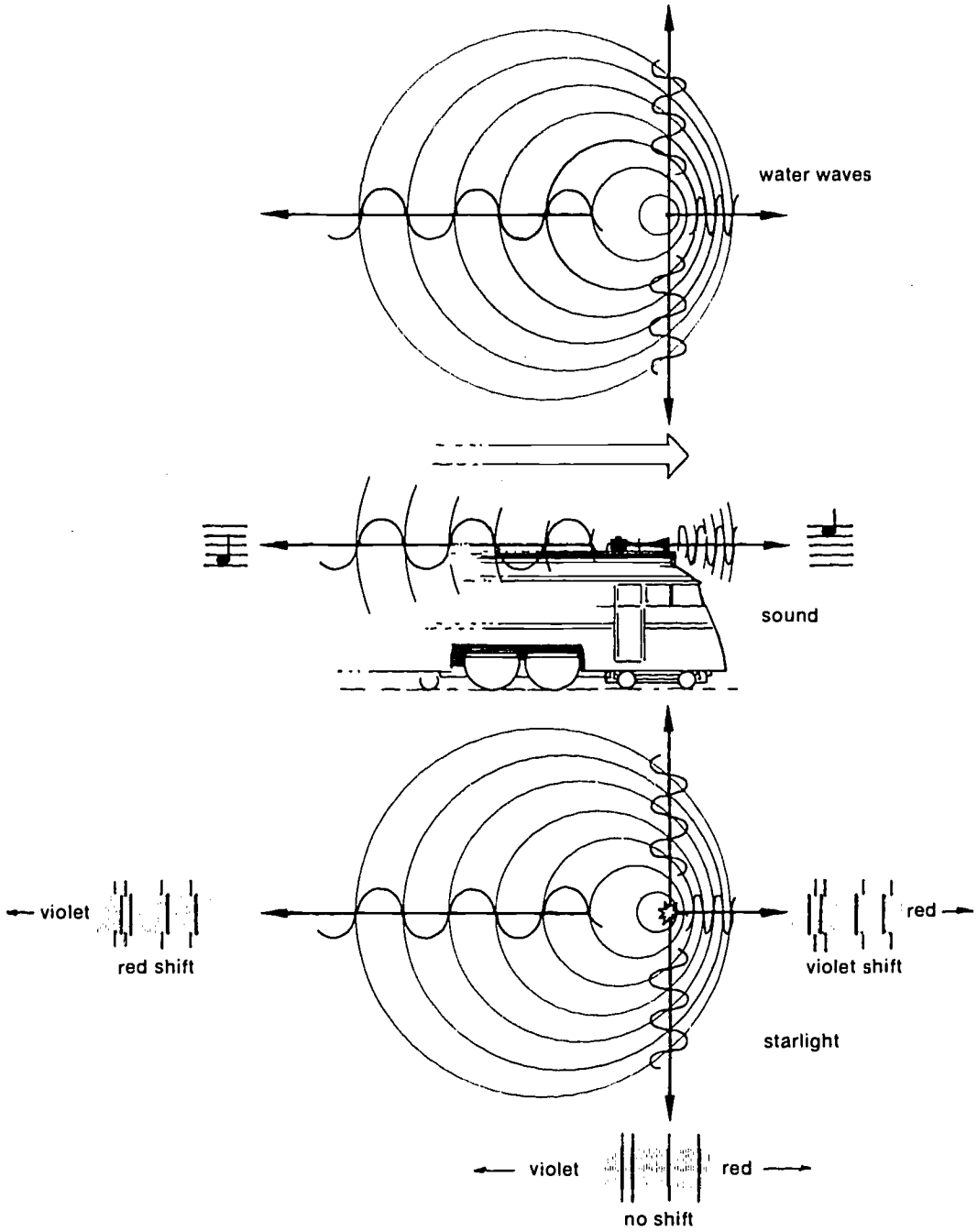
What can cause absorption lines to shift to different wavelengths? Can the atmosphere of a star change its atoms so that they block out different wavelengths at different times? In their search for answers to the puzzle of shifting lines, astronomers found a clue in the work of Christian Doppler (DOP-ler).

Doppler's main interest had been with sound waves. In 1842, he proposed a solution to a noisy puzzle. You have heard a locomotive whistling as it passes you at the station. Perhaps from the roadside you have heard a car sounding its horn as it sped by. The pitch of the sound—its wavelength—changes as the car passes you and goes on. Doppler was able to explain these facts. His explanation for sound waves can be observed by studying water waves on a ripple tray.

Set up your ripple tray again. Use one-fourth of an inch of water and wads of cotton around the sides to absorb reflections. Make waves with the eraser end of a pencil, and focus the overhead projector until the waves are easily seen.



Make rapid point-source waves while you move the pencil steadily across the tray. Make several trips back and forth. Move the pencil across the tray at first one speed, then another. Observe the pattern of wavelengths in front of the moving pencil. Watch the pattern of wavelengths that trail the pencil. What is the difference?

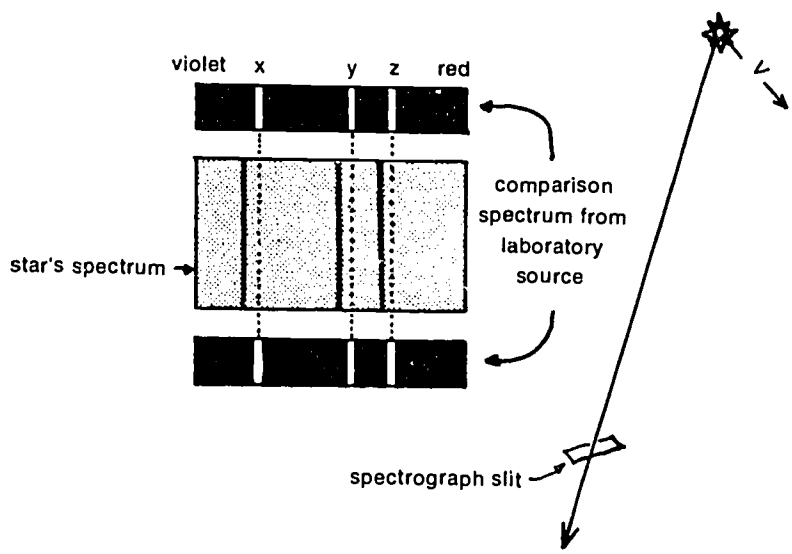


It was Doppler's discovery that waves reaching you from a moving source can have wavelengths different from the waves emitted by a stationary source. You receive a higher pitched sound from a train that is approaching you. When the train is receding from you, the whistle sounds lower pitched. When the source is approaching you, the wavelengths are shorter than the original wavelength; when the source is leaving you, the wavelengths are longer than the original wavelengths.

You have observed that water waves also show the Doppler effect. And astronomers applied Doppler's explanation for sound waves to waves of light. The waves of light striking your eyes from an approaching star are slightly shorter than normal; from a receding star, they are slightly longer.

## MEASURING CELESTIAL VELOCITIES

Doppler went one step further. He figured that the greater the speed of an approaching source, the greater would be the shift of its absorption lines toward the violet. The greater the speed of a receding source, the greater its red shift. The rate at which a light source approaches or recedes is called the *radial velocity*.




How does an astronomer put the Doppler effect to work? He photographs the spectrum of a star, a nebula, a galaxy, or any other object. Suppose that he gets particularly strong dark lines, which we'll call *x*, *y*, and *z*. He then compares the dark lines on his spectrum photograph

to emission lines produced by a radiating laboratory source that is right in the telescope dome with him. He knows that this *comparison source* isn't moving, but maybe the star he just photographed is moving. How does he find out? He carefully measures the amount by which the stellar lines *x*, *y*, and *z* are shifted in Angstroms. Then he can do a bit of arithmetic and work out the rate at which the star is approaching or receding—its radial velocity. Here is the Doppler formula:

$$\text{radial velocity} = \frac{\text{wavelength shift}}{\text{laboratory wavelength}} \times \text{speed of light}$$

If the laboratory wavelength of a spectrum line is 5000.0 A, and if its recorded wavelength is 4999.0 A, then the measured shift is 1.0 A toward the violet. Now you can figure the radial velocity.

$$\text{radial velocity} = \frac{\text{shift}}{\text{wavelength}} \times \text{speed of light}$$

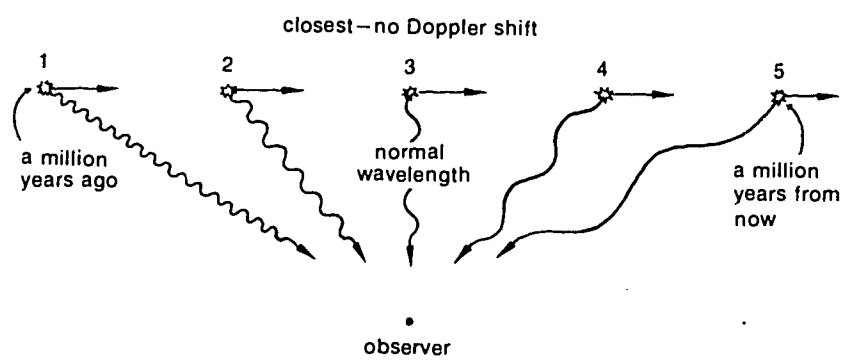
$$= \frac{1.0\ \text{A}}{5000\ \text{A}} \times 186{,}000\ \text{mi/sec}$$

$$= 37.2\ \text{mi/sec}$$

The light source is approaching the earth at about 37 mi/sec.

Astronomers know the radial velocities of more than 10,000 stars from such measurements. Vega is approaching the solar system at 9 mi/sec, and Sirius at 5 mi/sec. Betelgeuse is receding at 13 mi/sec.

The Doppler shift doesn't tell us anything about a star's motion across the sky sideways with respect to the observer. All that is revealed is how fast the star is getting nearer to us or farther away.

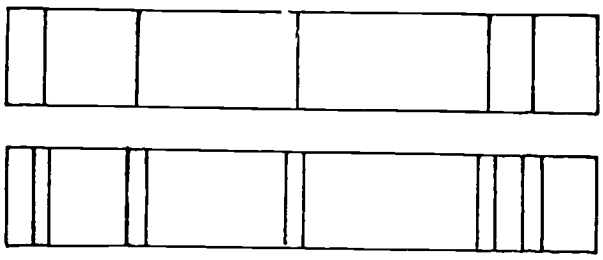


In the preceding diagram, a star overtakes and passes an observer. At position *1* its motion is most nearly in the direction of the observer. He detects a large radial velocity of approach from the Doppler-shortened wavelengths. The Doppler-shifted wavelengths become longer (position *2*) as a star catches up with the observer. At position *3*—its moment of passing the observer—all of the motion is sideways. Here the star is not moving toward the observer at all, and there is no Doppler shift. At positions *4* and *5*, after the star passes and drifts off into the distance, the motion appears to be directed more and more away from the observer. The Doppler-shifted wavelengths lengthen until, in time, practically all of the star's velocity appears to the observer as radial velocity.

The Doppler effect has become very important in attempts to decipher the message of starlight. Let's turn to just a few of the many celestial puzzles it has helped astronomers solve.

## PAIRS IN A PINPOINT

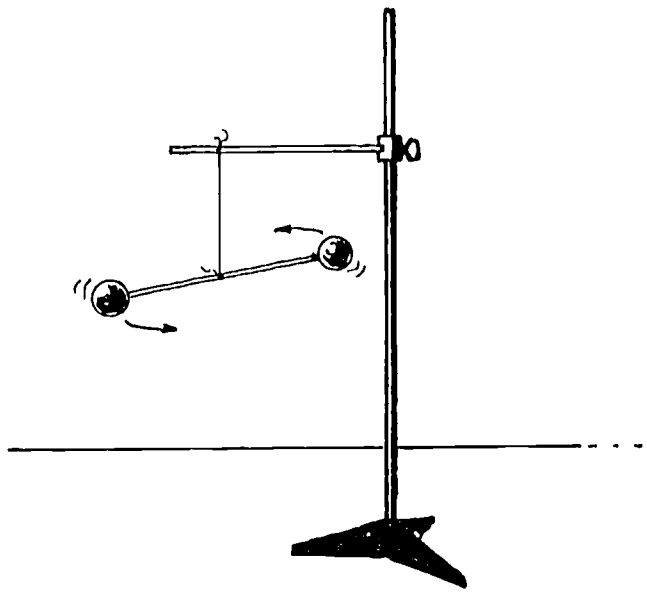
Back to the puzzle of Mizar A. When the absorption lines split, one portion of each line shifts toward the violet end of the spectrum, indicating slightly shorter wavelengths. The second portion of each line shifts toward the red, showing slightly longer wavelengths. Is Mizar A both coming and going?



To help you visualize what is going on at Mizar A, fasten a ball of modeling clay at each end of a pencil. Tie a piece of string to the center of the pencil and suspend the balanced clay spheres.

Tap one piece of clay so that the spheres rotate around each other slowly. Watch them carefully. When, in their orbits, is one ball approaching while the other recedes? When are the spheres traveling sideways so that they are neither coming nor going as far as you are concerned?

To an observer, even with the most powerful telescope, Mizar A appears as a single point of light. But Mizar A must actually be two stars, orbiting each other in about 20 days. With the spectroscope, the different velocities help to separate the spectra of the orbiting companions.



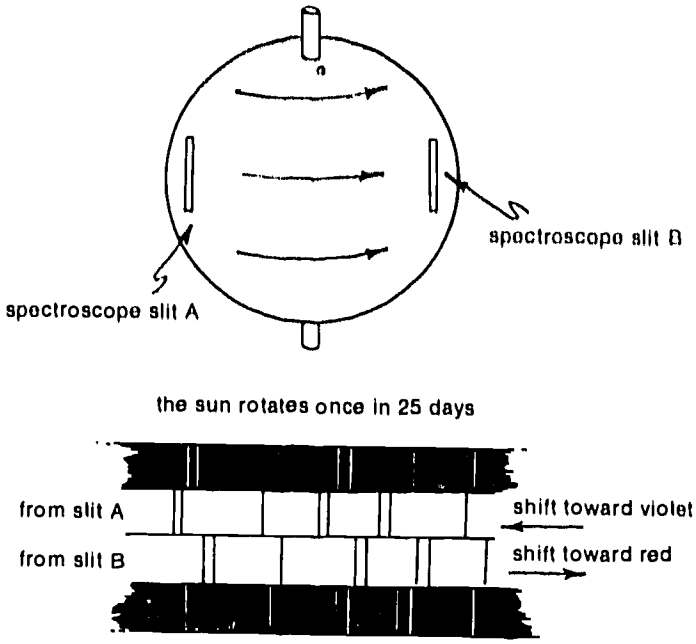
Astronomers have discovered other star-pairs besides Mizar A—stars so close together that they appear as a single point of light even with the most powerful telescopes. By studying the separation of the dark lines from time to time, they can learn the difference in the radial velocity of the two stars. This knowledge gives them some idea of the orbits of the two stars around each other—all without being able to see more than just one pinpoint of light.

## STELLAR SPIN

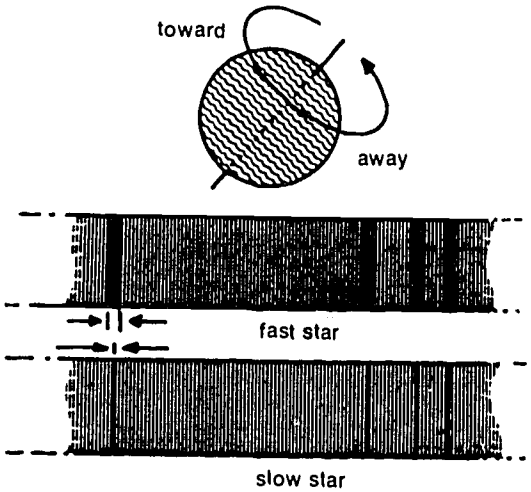
Some stars have dark spectral lines that are surprisingly thick. Each line is wide enough to cover several Angstroms. Most stars have much thinner lines. Why is there this difference?

From the motion of its sunspots day by day, we can tell that the sun takes 25 days to rotate once around its axis. Even so surface gases at the equator are moving at 1 mi/sec because of rotation. One side of the sun's disk is moving toward us, and one side is moving away. The

spectrum lines from the side approaching us are slightly Doppler-shifted toward the violet; those from the side receding from us are slightly shifted toward the red. These differences can be detected by pointing the slit of a spectroscope at different parts of the sun's disk.




How about other stars? We can see them only as points of light. There can be no hope of sampling the light from first one side and then the other, as we can do with the sun. Starlight entering the spectroscope is a mixture of light coming from the entire stellar surface facing the earth.



Suppose a star is spinning rapidly. What would you expect its absorption lines to look like? The part of the rotating star moving toward us most swiftly would send light with the most violet-shifted lines in the mixture. Light from the receding side would contribute red-shifted lines to the mixture. Light from different parts of the star would show the sodium line with slightly different wavelengths. In the spectroscope the sodium absorption line would be a mixture of these Doppler-shifted lines—broadened and spread out. The faster the spin, the more spread out are all the spectrum lines.

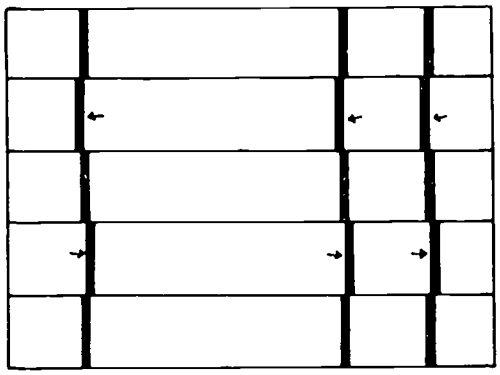
From the widths of absorption lines, astronomers have found stars that rotate faster than 300 miles per second at their equators. Such stars are on the verge of flying apart. However, most stars are slow spinners like the sun.

Thick lines give us the clue to rapid rotation. If we were not able to study the spectrum of starlight, we would never know that there were rapid spinners among the stars.

## SWELLING AND SHRINKING

Many stars change in brightness in a rhythmic way. Now they are brighter, later they are dimmer, and then once again they are at their brightest. Among the most celebrated of these variable stars are the *Cepheids* (SEE-fee-idz).

This group of stars is named after the first one discovered—star Delta in the constellation of Cepheus (SEE-fee-us). The light variation of such stars prompted astronomers to look at their spectra to see if they could find any clues to the nature of the changes in light.



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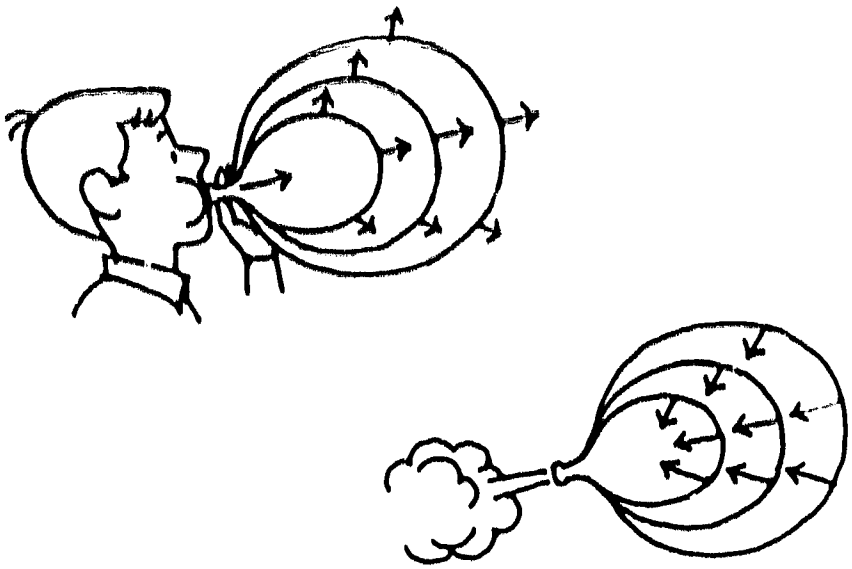
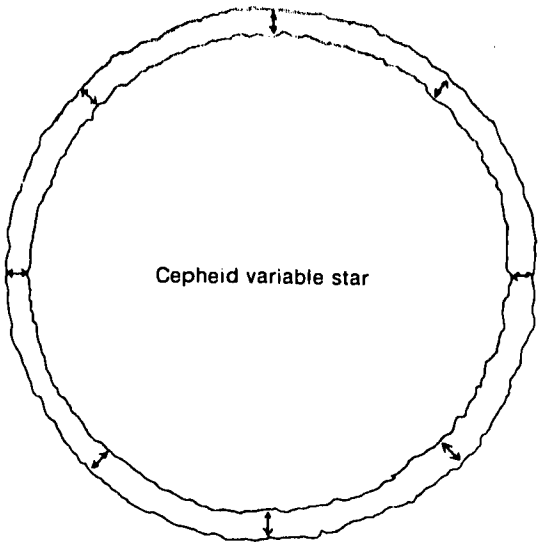
They found that all the spectral lines shift back and forth, toward the red, and then toward the violet, and back again. The time for the line to make one full trip from shortest to longest wavelength shift and back again turned out to be identical with the period of light variation.

Imagine a balloon slowly being inflated a foot or two before your eyes. Does the near side of the balloon have any radial velocity as far as you are concerned? Is it approaching or receding?



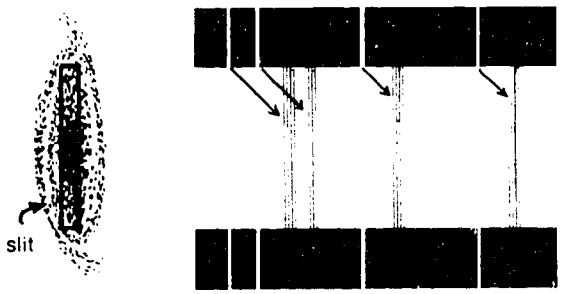
Next imagine air being slowly let out of the balloon. Once again note the radial velocity of the near side.



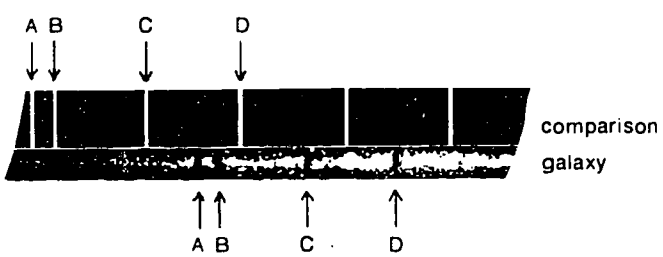
All the evidence indicates a periodic swelling and shrinking of the Cepheid variable stars. Accompanying these changes in size are changes in the amount of light the stars give off. A careful study of the Doppler shifts shows the difference between the radius of the star when it is brightest and the radius when it is smallest. These stars are usually about a tenth bigger in radius at maximum size than at minimum.

## DENIZENS OF THE ULTRA-DEEP

By using their largest telescopes, astronomers are able to photograph the faint light of distant galaxies. The light is so feeble that it takes a time exposure lasting several nights to get a spectrum. What is found when they study these spectra?

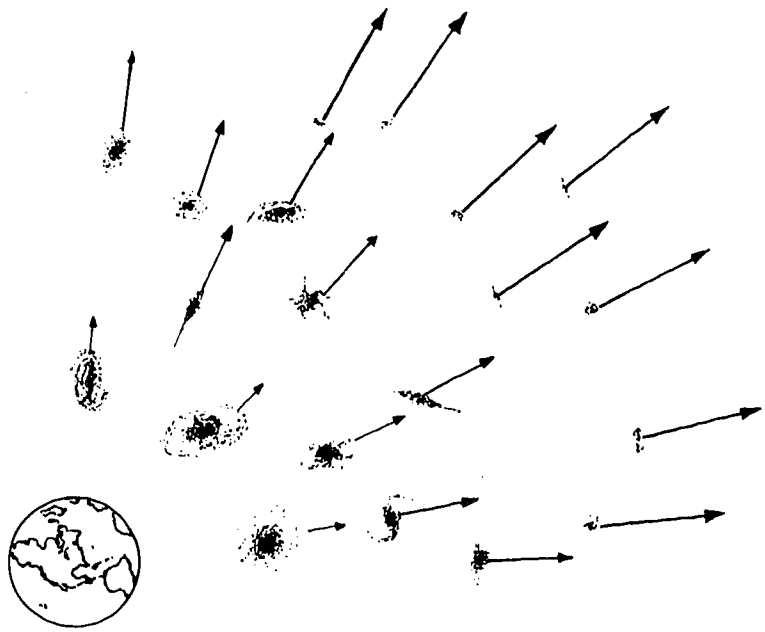



The few fuzzy absorption lines that appear are far out of place. They are shifted to the red. The shifts indicate that these galaxies are receding from us. From their measurements of Doppler shifts, astronomers have succeeded in finding the radial velocities of about a thousand galaxies.




The nearby Whirlpool Galaxy in Ursa Major is receding at about 260 mi/sec. The more distant Sombrero Galaxy is rushing away at 710 mi/sec. Farther afield in the constellation of Coma Berenices (KO-muh

bear-uh-NIGH-seez), some galaxies are moving away at about 4200 mi/sec. The biggest Doppler effect yet measured for galaxies shifts lines far across the spectrum. What were ultraviolet photons on departure are recorded here on earth in the red part of the spectrum. The velocities of some galaxies have been found to be close to the speed of light itself.



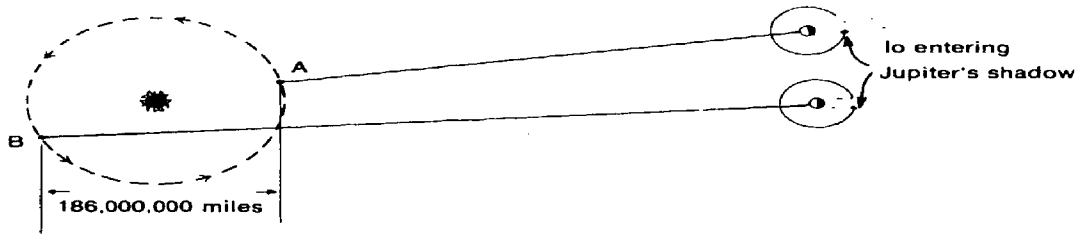
What is the meaning of these red shifts in the spectra of galaxies? In comparing these speeds, astronomers have discovered some exciting facts. First, almost all the galaxies are racing away from us. Second, the farther away a galaxy, the faster it is speeding outward. Most astronomers interpret these observations as evidence that the whole universe is expanding—that all the galaxies are continuously moving further apart.

## DOPPLER ALL THE WAY

Astronomers have learned much about the motions of celestial objects from shifted spectral lines. Broad lines hint that some stars rotate very rapidly. Some absorption lines that shift back and forth reveal information about close star-pairs; others provide clues that some stars swell and shrink. Doppler shifts show the radial velocities of stars. We would have no conception whatever of the expanding universe of galaxies if it weren't for the to-and-fro effect first proposed by Doppler.

## ON YOUR OWN

Study the drawing below. It shows the earth circling the sun and Io (EYE-oh), one of Jupiter's moons, orbiting Jupiter. By measuring the time between Io's eclipses—when it enters Jupiter's shadow—astronomers know that the satellite orbits Jupiter in 42 hours, 28 minutes. As the earth travels from *A* to *B*, however, each eclipse seems to occur a few seconds later. By the time the earth is at *B*, eclipses are lagging behind by 16 minutes, 38 seconds.




In 1676, Ole Roemer (OH-lee ROE-mer), a Danish astronomer, said that this time lag occurred because light had to travel a greater distance to reach the earth at *B* than at *A*. Use these facts to measure the speed of light. Remember that the earth is about 93 million miles from the sun.

Suppose an astronomer photographs the spectra of several of the stars in Cassiopeia. He measures the shift of a line at 5000 A. Here are the tiny amounts that the line might shift for each star. Compute radial velocities, using Doppler's formula. Copy the following table and fill in the blank spaces.

| *Star in Cassiopeia* | *Shift* | *Direction* | *Radial Velocity (− = toward, + = away)* |
|---|---|---|---|
| Alpha | .07 A | red | + 2.6 mi/sec |
| Beta | .20 A | violet | |
| Gamma | .12 A | red | |
| Delta | .12 A | violet | |
| Epsilon | .13 A | red | |

CHAPTER 11

# The Universe of Light

All we know about the stars is carried in the light they send us across the depths of space. The information contained in that light is detailed and revealing. Only recently have astronomers learned how to decode the scrambled message of starlight.

First, physicists observed how light behaves. Models of light were invented. Physicists and chemists used prisms and gratings to study the spectra of elements, just as you have in this book. Models of the atom were constructed. Astronomers then could do some decoding. They could begin to understand the nature of stars and of other objects emitting radiation into space. There is still more to learn — much more. The job of astronomers is an unending one.

Nearly everywhere astronomers have looked, they have found matter in the gaseous state. The dark lines in the spectra of stars and the bright lines in certain nebulae both point to the gaseous nature of the stars and the stuff between the stars. The only solid matter that astronomers find in the universe is in the tiny planets and in the interstellar dust grains.

From what we know so far about the universe, all matter except about one part in a thousand is in the form of gas.

What are the stars? The appearance of their spectra established in the last century that the stars are distant suns, just as the sun is a nearby star. Some stars are hot; some are cool. Some stars emit more photons than the sun; some emit less. Some stars are big; some are small. But they are all the same kind of object. Each one is a hot radiating sphere of gas.

What are the stars made of? Atoms. And atoms are atoms the universe over. Their spectra tell us so. What kinds of atoms? If you said the universe is all hydrogen, you wouldn't be far from wrong. Ninety per cent of all the atoms in the universe are hydrogen; almost all the rest are helium atoms.

Along with these two elements, the stars and interstellar matter contain just those other elements that we have here on earth. There are no

brand-new kinds of elements we don't know about here at home—not even in remote galaxies. Their spectra tell us so.

The matter of the universe is the same all over—in flashing meteors, in the atmospheres of other planets, in the stars, in glowing nebulae, and in the farthest galaxy we can detect.

Wherever a spectrum line appears at a wavelength other than its usual one, we can, with the help of Doppler's suggestion, say something about how the source is moving. Double stars orbit rapidly around each other. Individual stars spin around their axis—some of them very fast. Some stars shrink and swell rhythmically.

Not too long ago the lines in the spectra of other galaxies were found to be shifted toward the red. The fainter and more distant galaxies have the largest red shifts. From what we can observe, the entire universe is expanding—the galaxies are flying away from one another.

At the outermost boundaries of the universe we know, there are dim systems racing away at nearly the velocity of light. The distance to such galaxies is somewhere around five billion light-years. We see those faint assemblies of stars as they were five billion years ago—about the time our own planet was born. What those galaxies are doing tonight, we shall never know. But the message of that starlight is speeding on its way toward us. Perhaps, at some far distant day, astronomers of another age will read it.