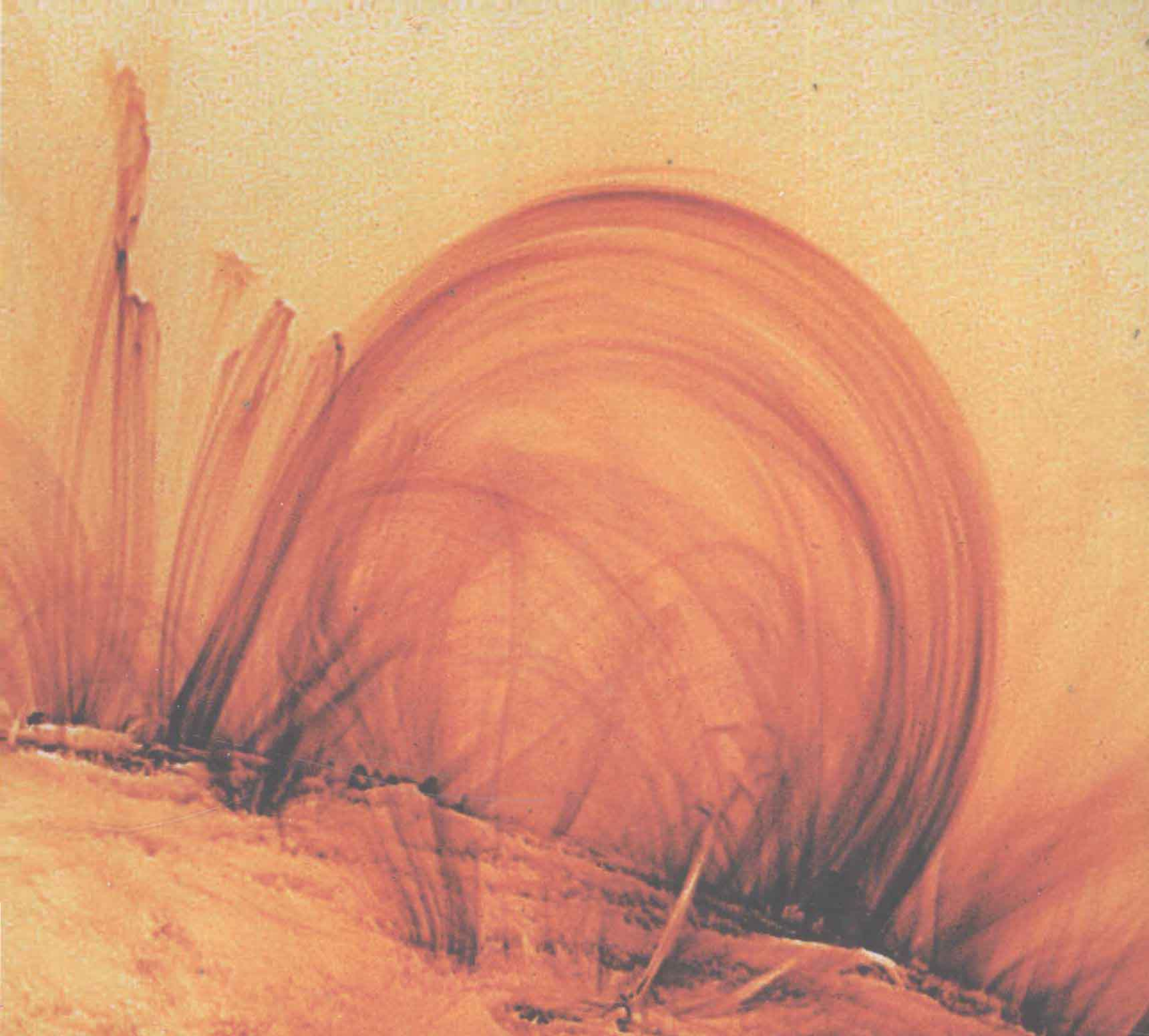

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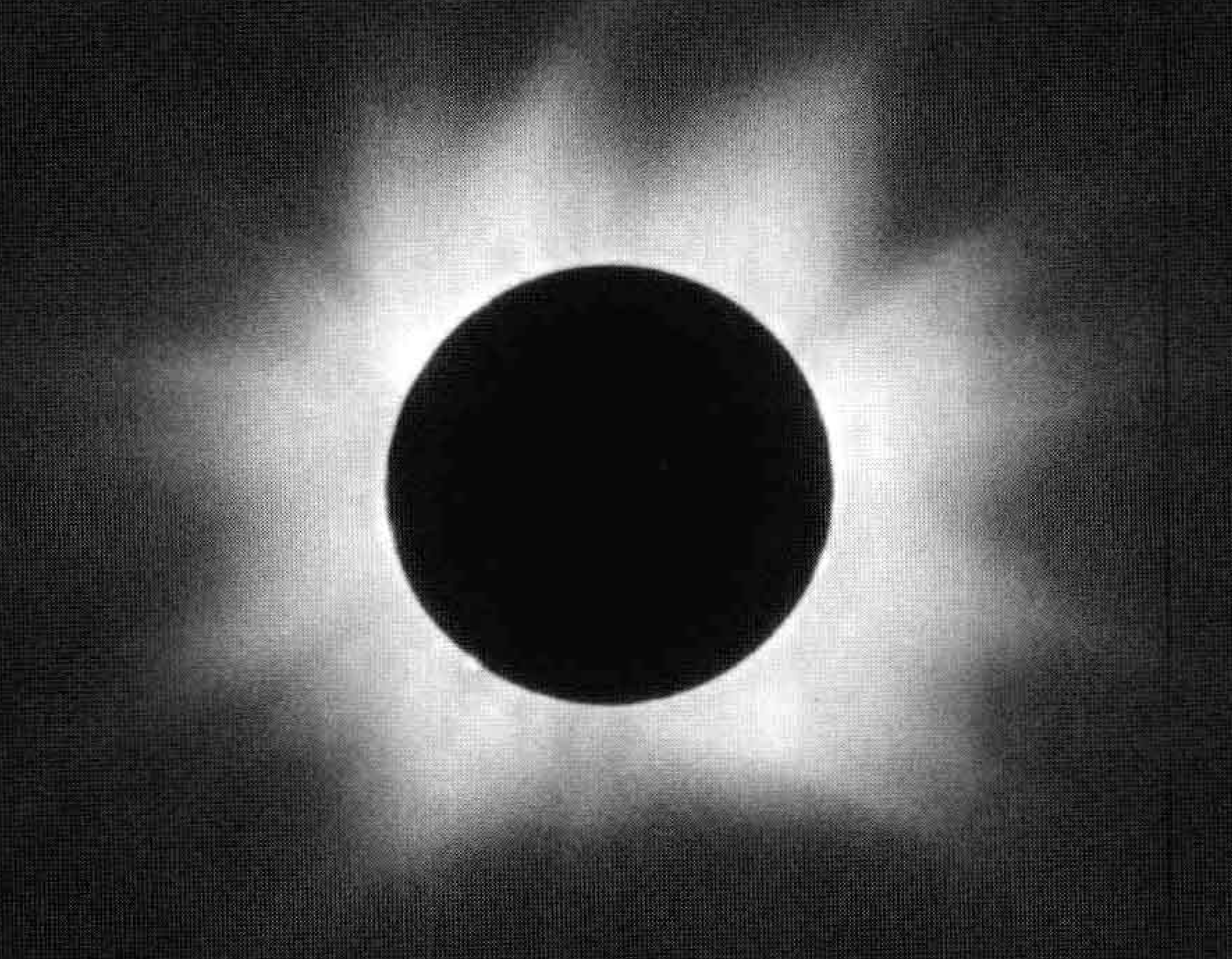

THE SURPRISING SCIENCE OF OUR SUN

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HARVARD UNIVERSITY PRESS
CAMBRIDGE, MASSACHUSETTS
LONDON, ENGLAND

Printed in the United States of America
Second printing, 2002

First Harvard University Press paperback edition, 2002

Title page illustration: the 1999 solar eclipse, a composite image
to emphasize the structure of the coronal streamers
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Library of Congress Cataloging-in-Publication Data

Golub, L. (Leon)
Nearest star : the surprising science of our sun /
Leon Golub and Jay M. Pasachoff.
p. cm.
Includes bibliographical references and index.
ISBN 0-674-00467-1 (cloth)
ISBN 0-674-01006-X (pbk.)
1. Sun. I. Pasachoff, Jay M. II. Title.

QB521.G65 2001
523.7—dc21
00-063213

Preface

Our Sun is a fairly ordinary star, a bit brighter than most but not exceptionally so. There are many stars much bigger and brighter, while most stars are smaller and fainter. The Sun is not an especially variable or active star, and it has no enormous chemical or magnetic peculiarities. It is not a very young star, nor is it old and nearing the end of its life. It is, in short, truly exceptional in only one way: it is very close to the Earth—in fact, at just the right distance to make life as we know it possible.

Most of us do not worship the Sun as did many in ancient civilizations, but we certainly should not take for granted the light and heat that it provides. Left to itself, the Earth would be a fantastically frigid rock at near absolute-zero temperature. If the Sun had been slightly more massive, its high temperature would have made the Earth's surface hot enough to melt lead. A smaller Sun would have left the Earth unbearably cold and possibly subject to high levels of radiation, since smaller stars tend to have higher levels of activity, giving off devastating ultraviolet and x-rays. Distance also matters. Had the Earth been closer, we might be as infernally hot as Venus; farther away and we might have been as cold and arid as Mars. We are in the position of Goldilocks, living at just the right distance from a just-right star.

Does this mean that the planet Earth is unique and that we live in a providential "best of all possible worlds"? There are dangers with this way of thinking, flattering as it is to human sensibilities, because it inadvertently fosters a certain complacency. Since indeed other planets in our solar system do not so far appear to support life, the implication is that life requires some fairly unlikely conditions in order to flourish. Yet granted that the probability of finding Earth-like conditions is small, the number of planets in the Universe is very large (probably billions in our galaxy alone). This obviously increases the statistical likelihood of habitable planets. On this view, the Earth is not so much providentially unique as merely *rare*.

This in turn implies certain responsibilities for its inhabitants. Since life as we know it appears to be possible within only a narrow range of conditions, it would be prudent to know as much as we can about the star that provides the bedrock conditions on which our existence is founded. Moreover, our newfound ability to alter the Earth's state on a global scale brings this need into sharp focus. For example, it is not enough for the Earth to be at the right distance from the Sun, and reflect back the right percentage of the solar light it receives. The Earth's atmosphere is also of major importance in determining the global temperature. Without it, the Earth would be colder by about 33°C (roughly 60°F), and therefore a frozen lump of ice. Right now, we are making small but significant changes to the composition of our atmosphere that may, within a short time, be large enough to produce major unpleasant effects. Do the natural variations in the Sun's brightness enhance or diminish these man-made effects? How do changes in solar activity affect the formation of ozone and atmospheric circulation and weather patterns?

This book explores the Sun in a comprehensive way for the nonscientific reader who wants to gain a general idea of the range and significance of solar physics. We will explain what is known about the Sun and how this knowledge is acquired, discuss the origin of the Sun's light and heat, and explore how the Sun evolved and what it will eventually become. We will pay special attention to cutting-edge research on the Sun's outer atmosphere—the part that we can see—and the effects of this solar atmosphere on the Earth and the space around Earth. Unlike other stars, which are mere points in the sky, the Sun is so close that we can see its surface. We see sunspots form and gigantic explosive events erupt out toward the Earth. Thanks to careful measurements of the Sun's surface motions, we have recently even learned to "see" inside the Sun.

Our book continues a fine tradition at Harvard University Press of descriptive books about the Sun for general audiences. We are proud to be following in the footsteps of Donald H. Menzel's *Our Sun*, with its first edition in 1949 and its second edition in 1959. We are also proud to be in the tradition of Robert W. Noyes's *The Sun, Our Star* (1982). There is much that is new on and under the Sun in the intervening years, and it is a pleasure to be able to describe it here. One of us (JMP) got his start in solar astronomy from both the distinguished scientists who were just listed. Donald Menzel took him, as a Harvard first-year student, to a total solar eclipse, which they saw from an airplane over the Massachusetts coast, and introduced him to the changing solar surface as part of a freshman seminar. Robert Noyes took him, as a graduate student, to his first professional observing experiences by inviting him to spend a summer working with him and with Jacques M. Beckers at the Sacramento Peak Observatory, Sunspot, New Mexico. That work developed into his thesis on the solar chromosphere, with Noyes as advisor. Subsequently, as the Donald H. Menzel Postdoctoral Fellow at the Harvard College Observatory, he worked with Professor Menzel in running a Harvard-Smithsonian expedition to the 1970 total solar eclipse in Mexico. He also collaborated with Dr. Menzel on eclipse expeditions to Prince Edward Island, Canada, in 1972, and to Kenya in 1973. It could not have been foreseen that Dr. Menzel's Harvard freshman seminar would begin JMP on the set of 31 solar eclipse expeditions that have taken him around the world.

This book attempts to render all technical material in ordinary English. The book closest to the present volume is Ken Lang's excellent *Sun, Earth, and Sky*. The main difference between the two is that we approach the story from a different point of view. Rather than present science as a series of prestigious accomplishments, we invite the reader into an open-ended process of discovery. We try to show what motivates the questions that are being framed in solar physics, and how instrumental developments and theoretical creativity work together in a dynamic way to gain better insight into the Sun. Our aim is to introduce a wide and diverse audience to the substance and importance of solar physics without straining the reader's patience. If we succeed in doing this, our efforts will be amply rewarded.

Although we primarily address nonscientists, we hope that technophiles may also find the discussions worthwhile, as we devote considerable attention to instrumentation. For those who want to pursue some of our topics in a more technical fashion and who have access to the World Wide Web or the Internet, the following are Websites specializing in solar or solar-terrestrial matters:

- The Solar Data Analysis Center at NASA
  http://umbra.nascom.nasa.gov/images/latest.html
- The Space Environment Center and space weather
  http://www.sec.noaa.gov
- The Transition Region and Coronal Explorer Satellite
  http://vestige.lmsal.com/TRACE
- National Solar Observatory
  http://www.nso.noao.edu
- Eclipse Working Group
  http://www.totalsolareclipse.net
- Today's Space Weather
  http://www.spaceweather.com
- Amateur Astronomy Solar Site with Daily Images
  http://www.lpl.arizona.edu/~rhill/alpo/solar

Finally, despite our best efforts, there will inevitably be typos and errors. We apologize for this in advance, and plan to maintain an errata page with an updated list of Web links and corrections at:

- http://www.williams.edu/astronomy/neareststar

We encourage readers to notify us of typographical or other errors they find: lgolub@cfa.harvard.edu or jay.m.pasachoff@williams.edu.

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Introduction

About 15 billion years ago, for reasons we do not yet understand, the Universe came into existence. Matter as we know it did not exist and even the forces by which bits of matter and radiation interact with each other were different than they are today. Our knowledge of physics is good enough now for us to calculate the conditions prevailing back to an incredible 10^{-45} seconds (a decimal point followed by a string of zeros with a 1 in the 45th place) after it all started. Of course, this does not get us all the way back to zero or before (if the word "before" has a meaning in this context), but we think we can speak with a fair degree of confidence about how things proceeded thereafter.

By 0.000000000001 seconds of age, the four forces of nature that now exist—gravity, strong and weak nuclear, and electromagnetic—were in place, and by the age of several hundred seconds the Universe contained the familiar, so-called baryonic, matter that continues to exist today, the stuff of which ordinary atoms are made. A major turning point occurred at the age of about 300,000 years, when the Universe cooled enough for electrons to combine with the available nuclei, which were mostly protons and helium. At this point, atoms started to form and it suddenly became possible for photons of light to travel long distances without being absorbed. Before this time the Universe was opaque, and our best telescopes will not be able to look back beyond this era.

Some time later, perhaps at an age of 1 billion years, galaxies started to form. Until then, there were few stars and therefore no sources of light—the Universe was in a dark age. Since galaxies consist of large numbers of stars, many billions of stars must have been forming, and we must assume that some fraction of them had planets as well. The Universe since then has changed only in some details—galaxies have evolved, the fraction of matter in heavy elements has increased a bit—but has otherwise looked pretty much the same as it does now.

The formation of the Sun is one extremely minute part of this history, the story of one tiny star among the trillions that have come and gone during the past 15 billion years. It is a relatively young star, only 5 billion years old and thus not of the first generation. This means that it, and the planets around it, contain heavier elements formed when earlier stars became novas and supernovas. These heavier elements—oxygen, silicon, iron, carbon, and so on—make possible certain side effects, such as organic life.

The Sun is by far the brightest object in our sky, and the difference between its presence or absence overhead is literally like night and day. It is clearly far away, although it took centuries to figure out just how far. How is it, then, that we can know anything about an object that is far away, extremely hot, and astoundingly large?

The answer is that the information is in the light. The science of spectroscopy allows us to analyze the solar light in detail (see Figure 1.1 for an example) and thereby learn about the elements that compose the Sun and their physical states. If we then also use high-resolution images of the Sun, we are able to find out what physical processes are occurring to produce the type of light that we see. We can even, with the help of a new method of measurement known as helioseismology, study the interior of the Sun as well.

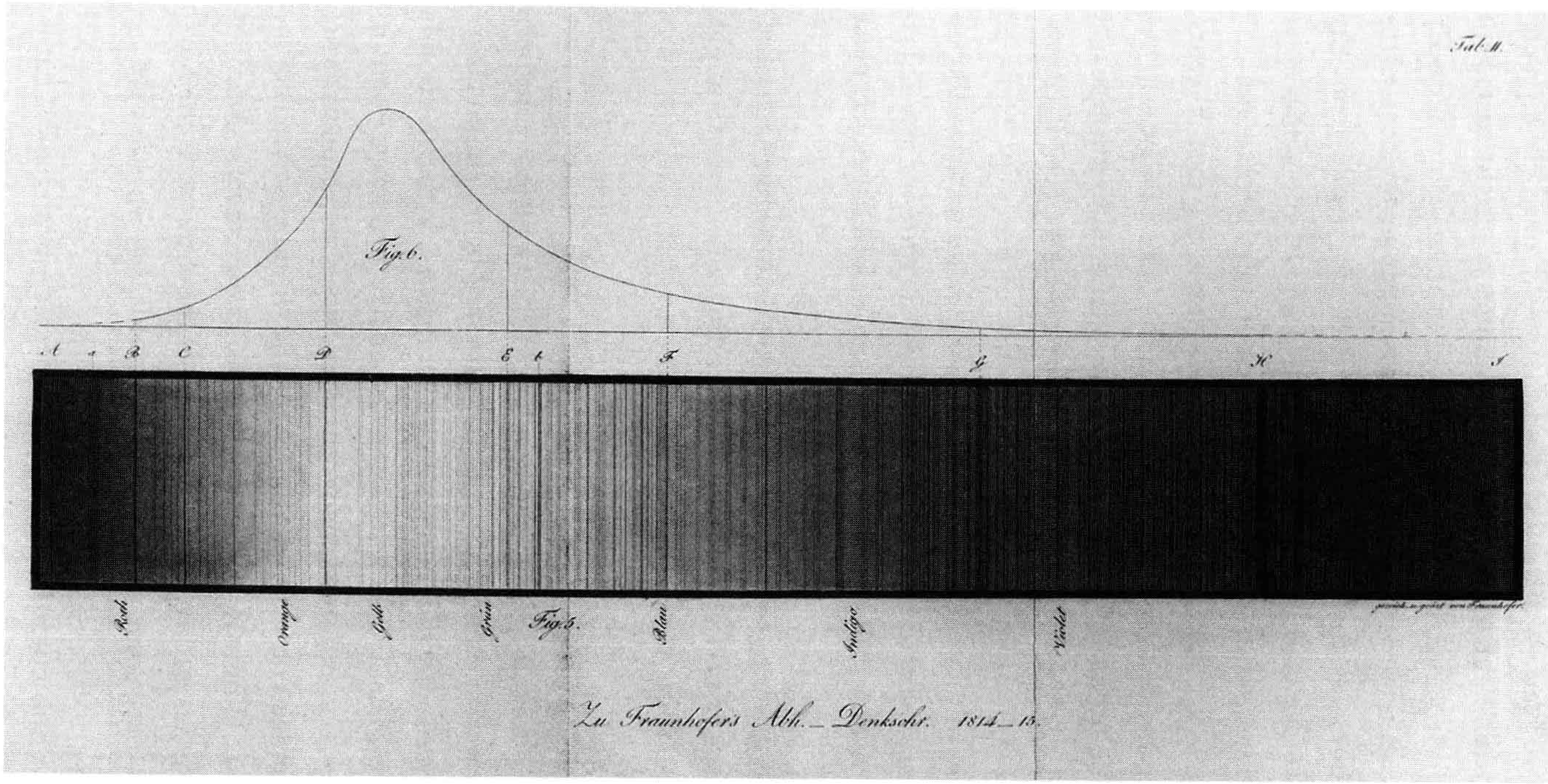

FIGURE 1.1 Josef Fraunhofer's photospheric spectrum, published in 1817. This was the first spectrum to show sharp, dark, absorption lines in the solar light. The locations and strengths of these numerous "spectral lines" provide information about the physical conditions on the Sun.

There is more than light coming from the Sun. Extremely high energy particles from large solar eruptions sometimes reach the surface of the Earth and are detected by terrestrial monitoring equipment. By putting instruments into space, we can extend the range of wavelengths available, enabling us to see solar phenomena not visible from the ground, and we can also intercept and study some of the actual solar material as it flows past the Earth at hundreds of miles per second.

Despite a rapid accumulation of new knowledge in the past 20 years, there is still a great deal we don't know about the Sun. The gaps in our knowledge have broad implications, because solar studies are relevant to almost all of astrophysics: many of the more exotic aspects of astronomy concerning distant stars and galaxies must, of necessity, be based on a foundation of theories and models developed and tested in the solar context. Our ability to explore the unfamiliar territory of intergalactic space reflects how well we understand the more familiar object close to home.

Solar physicists do not normally spend their days asking each other the big questions. But a group of them attending a conference might, after dinner and some wine, ask each other:

- Do we really know the energy source of the Sun? One of the great triumphs of astrophysics in the first half of the twentieth century was the understanding that the Sun is powered by thermonuclear fusion—essentially the same process that makes a hydrogen bomb, but on an enormously larger scale. The nuclear reactions ought to release a certain number of sub-atomic particles called neutrinos; these are indeed detected, but in far smaller numbers than they ought to be. Where does the problem lie? Is our understanding of nuclear physics wrong? Are our models of the interior of the Sun wrong? Is there some oddity about neutrinos that we don't yet know?
- Why is the Sun not just a bland, featureless, glowing ball? That is, why does the Sun have sunspots, flares, and a corona? Why does the activity come and go in an 11-year cycle? We now believe that

all of these effects are caused by strong magnetic fields generated deep inside the Sun. Do we understand how and why the Sun generates magnetic fields? How prevalent are magnetic fields on other stars, on planets, throughout our galaxy and other galaxies? How do magnetic fields affect the formation of these? What role do fields play in more exotic objects, such as black holes, pulsars, astrophysical jets, and quasars?

- Is the Sun changing in ways that affect the Earth's global climate? Does the sunspot cycle produce climate changes on Earth? Are there longer-term changes in the Sun that might have produced the ups and downs of climate that we find in geological records? More important, will changes in the Sun in the future produce climatic effects on the Earth? Will man-made effects dominate over the solar changes, or will they reinforce each other to produce a major climate disaster?

The Sun's Physical Parameters

Questions such as these, which fuel the excitement of solar research, require a long apprenticeship in learning what has been established so far about the Sun's basic parameters. This chapter and the next two will give the reader a taste of this process by reviewing the fundamentals.

Here are some of the basic facts:

- The ratio of the Sun's diameter to that of the Earth is: 109.
- The ratio of the Sun's mass to that of the Earth is: 333,000.
- The ratio of average solar density to that of the Earth is: 1/4.
- The ratio of the Sun's mass to the sum of all the masses of all the planets is: 744.

What do these numbers mean? The Sun is *big* by Earth standards, over a hundred times the diameter, meaning more than a million times the volume. The smallest features that we can see on the Sun with the naked eye or with low-power telescopes, such as sunspots, are usually as big as the Earth.

The Sun is also very massive, having over 300,000 times more total matter than the Earth. Since the Sun is a million times bigger than the Earth, if it had the same density as the Earth, it would be a million times more massive. But its density is low, only one fourth that of the Earth (giving it about the same density as water). The implication of the low density is that the Sun is not made of the same stuff as is the Earth. It is mainly hydrogen, the lightest element, followed by helium, the second lightest. (This fact was first realized by Cecilia Payne in her 1925 Radcliffe Ph.D. dissertation, but it was so contrary to expectation that, under pressure, she labeled her result "spurious.")

The Earth is made mostly of heavier elements, with very little hydrogen or helium, even though modern cosmology tells us that these two light elements are the most plentiful by far in the entire universe. It would seem that during the formation of the solar system something caused planets like Earth to end up with more heavy elements, or with fewer lighter elements. Today's explanation is that the smaller planets such as the Earth did not have enough gravitational pull to hold onto very much hydrogen; it escaped back into space and we ended up mainly with the relatively rare heavy elements—oxygen, silicon, magnesium, and iron being the most abundant. The large planets in the solar system, such as Jupiter and Saturn, retained these lighter elements and have far lower density than the small inner "rocky" planets. In the Sun, hydrogen and helium together make up 98 per cent of the total mass.

The fourth datum on the list explains why the Sun is the center of our solar system: it has over 700 times as much mass as all of the solar system planets combined, including comets and asteroids. All of these objects form a self-gravitating system. Floating freely in space, they are held together by their mutual gravitational pulls and are relatively uninfluenced by other distant masses. In such a system, if one of the masses is much larger than the others, it will be nearly unmoved by the gravitational pull that the other bodies exert on it. For our solar system, the Sun has about 99.9 per cent of the total mass. This means that in the gravitational tug-of-war among all these bodies orbiting around each other, it is a very good approximation—to an accuracy of about 0.1 per cent—to say that the Sun remains stationary at the center of the solar system and all of the planets, asteroids, comets, and so on, orbit around it.

The Distance to the Sun

As a warm-up exercise, we start by trying to figure out just how bright the Sun really is. We can get some idea by making measurements here on Earth, if we measure the brightness here and if we also figure out how far away the Sun is. The technique is this: Assume that the Sun radiates equally in all directions, so that our local data are representative of what anyone, anywhere, at our distance from the Sun would measure. This distance defines a spherical surface enclosing the Sun and having a radius equal to 1 A.U. (Astronomical Unit), the average distance between the Earth and the Sun. If we then take our measured value and multiply it by the surface area of this enclosing sphere, we have determined the total power emitted by the Sun.

In order to make this calculation, we need to know the radius of the sphere, that is, the distance between the Earth and the Sun. The problem is that no direct measurement is possible. What we can do from our terrestrial location is to measure angles between objects and use these data to figure out *relative* distances. By measuring angles we can lay out the geometric pattern of objects in the solar system and determine, for instance, that the Sun is 400 times as far away as the Moon. So if we know the distance to either one of them, we know the distance to both.

The first person known to have made such a measurement was Aristarchus in the third century B.C.E., who measured the angle between the Sun and Moon when the Moon was exactly half full. If the Sun were infinitely far away, this angle would be 90 degrees; with the Sun at a finite distance, the angle is slightly smaller, as shown in Figure 1.2. With this method, the number calculated for the distance of the Sun is extremely sensitive to the measured value of the angle. Aristarchus

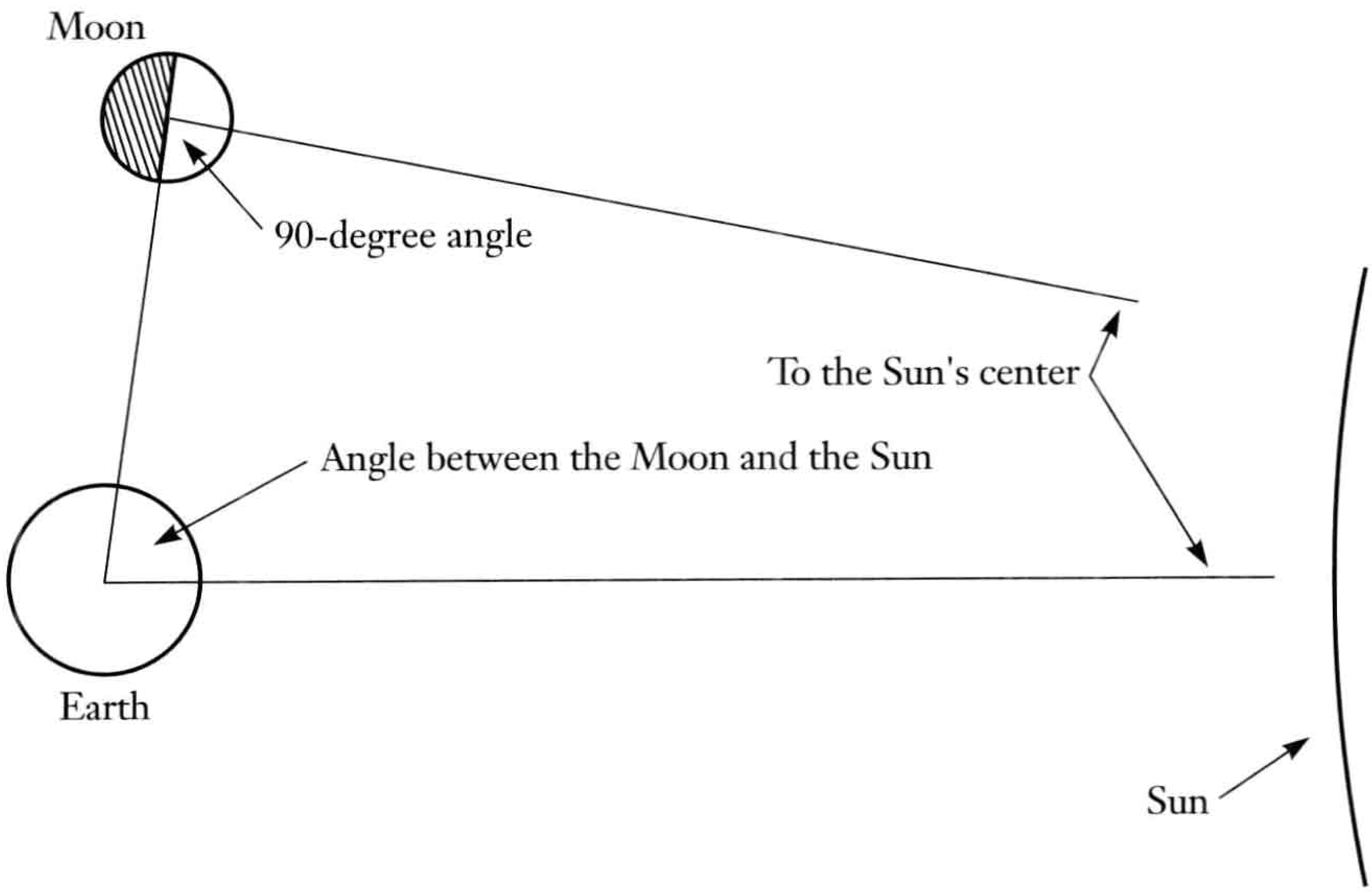

FIGURE 1.2 The geometrical relationships between the Earth, Moon, and Sun used by Aristarchus to determine the distance to the Sun.

measured 87 degrees, whereas the value is really more like 89.85 degrees. His calculation said that the Sun is only 18 times farther away from the Earth than is the Moon, rather than 400 times farther. Still, the method he used was sound, and with more accurate measurements of this sort we can determine the relative distances of the Sun, Moon, and planets quite well.

But we still do not know the scale of this pattern of relationships. How do we ever find any absolute distances? The answer to this problem turned out to require the invention of extremely accurate clocks. Why clocks? Because the method used was triangulation from widely separated points on the Earth, and the method requires not just a measurement, but an absolute determination of when the measurement is made.

Transits of Venus

In astronomy we speak of parallax, rather than triangulation, to denote the well-known phenomenon that two objects line up differently along the line of sight for one observer than for another. For example, during a solar eclipse an observer at one location might see the Sun and Moon line up perfectly, so that the eclipse is total. But an observer some distance away might be able to see past the edge of the Moon for a partial view of the solar disk; for her, the eclipse will not be total.

We have known the relative distances among the planets for quite some time—the values have not changed much since the days of Copernicus. We have also known how fast the planets move around in their orbits, so that the angles between them and how these angles change with time has been known for many years. But in order to progress from a relative diagram to one whose absolute size is determined, we need to know the true length of any one piece of the figure; we will then know all of the lengths. Parallax can be used to make this measurement.

We do have access by direct measurement to one length: the size of the Earth, or more to the point, the distance from one side of the Earth to the other. All we need then is to line up two objects from one side, then from the other, and measure the size of the angle between these two perspectives, and we will know the absolute scale of the solar system. But what to use to make the measurement?

In 1716, Edmond Halley—who not only plotted the orbit of the comet that bears his name, but who also was the first accurately to predict the path of a total solar eclipse—pointed out that the passage of the planet Venus across the face of the Sun could be used to provide the needed marker. There had been a pair of transits of Venus in 1631 and 1639, but no useful measurements were made. The next pair of transits would occur in 1761 and 1769, and Halley, knowing he would not live to see them, urged future astronomers to make the extraordinary efforts needed to obtain the crucial measurements from widely separated parts of the Earth.

Time enters into the measurement because the contact between Venus and the bright disk of the Sun occurs at different times at the two separated sites. If we imagine that the line joining the edge of the Sun to Venus is continued out until it hits the Earth, then this line sweeps