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Jay M. Pasachoff and Michael A. Covington
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INTRODUCTION

DARKNESS SWEEPS THE EARTH

Through a filter, we could see that the moon was starting to cover the sun. The solar eclipse had begun. We had not travelled thousands of miles to Hawaii and brought three tons of equipment in vain. Nobody was to jump from behind a palm tree and shout "April fool." The most exciting spectacle that is ever visible on earth would soon occur: a total eclipse of the sun. The new day would soon turn back to night.

Dozens of scientists and tens of thousands of tourists had come to mid-Pacific in 1991 to watch, study, and marvel over the spectacular phenomena that occur when the moon completely hides the sun. In this book, we will tell you how to observe and photograph this kind of eclipse as well as the other kinds that occur. Over the next decade, many solar eclipses – both total, in which the sun is entirely hidden, and annular, in which a ring of sunlight remains – will be visible from one place or another across the globe. Further, many lunar eclipses, in which the moon is partly or entirely hidden by the earth's shadow, will be widely visible. All are fun to see.

Between us, we have seen dozens of eclipses, and we are glad to share our experiences with you. Sometimes we will write in the voice of one of us; at other times, we will write together. We hope to convey both technique and spirit.

By two thousand five hundred years ago, the Babylonians had found that solar eclipses repeated in a pattern. Taken by themselves, the patterns in the sky followed by the sun and the moon do not mesh. But when the earth has gone around the sun exactly 19 times, measured by the number of times the path of the sun in the sky crosses that of the moon, the moon has gone around the earth exactly 223 times. As a result, the sun and moon come back to the same place in the sky at exactly the same time. In fact, even the moon's distance from the earth, which varies because the moon's orbit is not round, is the same after this interval, which is called the "saros." The Babylonians had discovered this saros interval of 18 years 11⅓ days. (Our leap years sometimes make the 11 days into 10 or 12.) The ⅓ day gives the earth a chance to rotate an extra ⅓ of the way around, so the eclipse that we had seen in Africa on June 30, 1973, was repeated for us in the Western hemisphere on July 11, 1991. The name saros wasn't given until the seventeenth century, when Edmond Halley supplied it. Halley referred to a misunderstood phrase in writing by the ancient-Roman scientist Pliny in choosing the word.

It must have been difficult for the ancients to find out about this saros interval, because many eclipses were on the wrong side of the world for them and because others were lost to clouds. Yet careful record keeping was obviously sufficient. It has even been suggested that one use of the giant set of stones at Stonehenge in England was as an eclipse predictor. Since the stones showed how the positions of the sun and the moon changed over time, the times when the sun and moon would be in a line could also be predicted. Though the idea is still controversial, markers could have been moved in a set of holes still known at Stonehenge to keep track of lengthy eclipse periods.

Myths from the Far East also indicate that the repetition of eclipses was understood. A traditional story is that the Chinese court astronomers Hsi and Ho overimbibed and failed to predict an eclipse, for which they lost their heads. This eclipse would have occurred at about 2000 BC, about when Stonehenge was being constructed, but the truth of the story is lost in the depths of time, and in the burning of all historical records that occurred in China. Often, the eclipse that calculations show took place on October 22, 2134 BC, is identified with the event, though the actual date is uncertain to within hundreds of years. Actually, Hsi-Ho was the name assigned to a sort of sun deity, with responsibility for preventing eclipses. They were supposedly from the Xsia dynasty, which is not historically established. In the words of F. Richard Stephenson of the University of Durham, it is "a tale without any foundation whatever."

The earliest prediction of the actual path of an eclipse across the face of the earth was made by the remarkable astronomer Sir Edmond Halley for the eclipse of 1715. This first known prediction of the actual path of totality came 10 years after Halley used the law of gravity advanced at his behest by Sir Isaac Newton to discover the periodicity of the comet that now bears Halley's name. So Newton's law of gravity not only revealed the truth about an important comet but also allowed us to obtain the accuracy needed to predict eclipses. The 1715 eclipse crossed southern England, and reports from various sites around the country are still being examined to find out just where the edges of the path were. Even data almost three hundred years old should be accurate enough to tell us whether an eclipse was total or not! Determining the path can tell us the size of the sun, which is significant because even small changes of the sun's size could lead to changes in our climate here on earth. Some scientists have suggested that small changes in the sun's size have been measured from eclipse to eclipse, but my own measurements at the total eclipse in Papua New Guinea in 1984 indicated that the uncertainties in measuring eclipse durations are too great to resolve the issue.

What was the earliest eclipse recorded? Some scientists think that an engraved tablet now in Damascus, Syria, records the eclipse of 1223 BC. If this translation is accurate, the tablet is the only surviving astronomical observation written in the Ugaritic language of Babylonia. The tablet refers to an event occurring at sunset, and it may not have been an eclipse after all. Since we don't know the Ugaritic names of the planets nor do we know the calendar they used, the identification of the tablet with an eclipse remains speculative. And even if it was an eclipse, it might not have been total. In 1993, an Orientalist and a historian of science from the University of Chicago concluded that the text does not correspond to a solar eclipse at all.

The ancient sightings of eclipses are still significant to us. To track down why, I went to see Stephenson in his office at the University of Durham. He has championed the use of ancient texts to determine the speed at which the earth rotates. "If the earth had rotated a little faster or slower than it does now," he explained, "the path of the eclipse would cross a different region of the earth. So we can find out very accurately how fast the earth had rotated on average ever since." When I was there, scientists were visiting him from Kuwait, Saudi Arabia, and other countries from which ancient chronicles sometimes reveal eclipse records. They continue to search for additional evidence of ancient eclipses in old chronicles. Said Said from the King Saud University in Riyadh explained, "This is a thorough search, volume by volume, of all sorts of chronicles that are well known by historians. The chronicles are in Cairo, Damascus, Baghdad and, for Islamic Spain, Córdoba. Nobody has done this before for Arab chronicles." The only way to find references, he explained, is to "wade through it." Stephenson disappointed me, though, when he told me that "Written accounts are common but it is very rare that there are illustrations." Also, the references aren't usually direct. "They sometimes express themselves in a poetic way." Also, eclipse illustrations were "virtually unknown in China too. It is the written word that seems much more potent to a chronicler."

Stephenson has investigated the details of the northern limit of the 1715 eclipse, which has been used to find the eclipse diameter. "I visited the northern site – in Darington – where the Hall is still standing. The easiest way in a small village is to approach the minister. He mentioned a couple there who took us on a tour to see the Hall where the marginal north limit was and also gave us a copy of the deed of sale of the Hall." Still, Stephenson concluded, "The observation is of interest but more of curiosity value than of real scientific interest. How do you interpret a marginal observation?" Stephenson, along with colleagues John Parkinson and

Leslie Morrison, found no trend in the solar diameter. "When you get down to things, there isn't in that material what you want."

The *Nuremberg Chronicle*, published in Nuremberg, Germany, five hundred years ago in 1493, has many references to eclipses and to comets. But the accuracy of the information declines the farther back in time it comes from, and it is impossible to determine whether the discussions of astronomical events are literal or figurative. Prof. R. J. M. Olson, an art historian from Wheaton College in Norton, Massachusetts, and I (JMP) travelled to Nuremberg to examine the handwritten manuscript from which the *Nuremberg Chronicle* was printed and from which the woodblock illustrations may have been copied. We found the sketches in these Exemplars too quickly drawn to be astronomically accurate. So the resulting woodblocks may be beautiful, but cannot be relied on for scientific accuracy.

Kevin Pang of Caltech's Jet Propulsion Laboratory has been examining ancient Chinese records, again to find eclipses that can reveal how fast the earth has been rotating. With Chou Hsiang, a UCLA professor of Chinese, he analyzed a sixth-century BC history book that contained old stories and dated one of the eclipses as that of October 16, 1876 BC. If this dating is correct, a day on earth was then 70-thousandths of a second shorter than today. Still, the written reference occurred more than a thousand years after the event. Pang, Chou, and colleagues have also found a reference on old tortoise-shell chips known as "dragon's bones" or "oracle bones" that read "Three flames ate the sun, and big stars were seen." They identified the event with the total eclipse of June 5, 1302 BC. The length of the day would then have been 47-thousandths of a second shorter than today.

Solar eclipses are so spectacular on earth because of a happy coincidence: the moon is both 400 times smaller than the sun and 400 times closer to the earth. If it were merely 400 times smaller, it would appear 400 times smaller in the sky. But because it is also the same 400 times closer, the moon takes up in the sky almost exactly the same angle as the angle the sun takes up. Thus when the moon passes in front of the sun, it blocks out the sun almost exactly. For no other solar-system planet and moon does such a lucky coincidence exist.

Largely because the moon's orbit around the earth is elliptical instead of round, the moon is sometimes farther away from the earth than average and sometimes closer. Thus it is sometimes smaller than average and sometimes larger. When it is larger than average and goes in front of the sun, the solar eclipse that results is relatively long. When the moon is smaller than average and goes in front of the sun, a ring of sunlight remains around the silhouette of the moon. Those eclipses are called "annular," because of this annulus (ring) of sunlight.

Solar eclipses always occur at new moon, since the lunar phase we call new moon simply results from the moon's being so close to the sun in the sky that only the moon's far side is receiving sunlight. Most months, however, the moon is above or below the sun's direction in the sky, so we do not have an eclipse. But no fewer than two nor more often than five times a year, the moon partly covers the sun, giving us a partial eclipse. And on the average of once every 1½ years, the earth, moon, and sun are in such a precise line that the eclipse is total or annular.

Only the total eclipses are spectacular, because the sun is so much brighter than the moon, the stars, or the everyday blue sky that shutting off only part of its light may not be obviously noticeable. The sun is a million times brighter than the full moon, for example. If even 1% of the everyday solar surface remains visible, the earth still receives 10,000 times more light than it does during full moon, and the sky remains blue and bright. Only when the sun is entirely covered – at a total solar eclipse – does the sky go dark. And only in such a dark sky can we see the faint outer parts of the sun. The halo of light that surrounds the sun, the corona, then appears readily to our view. It is about the same brightness as is the full moon, and is equally safe to look at. By contrast, during a partial or annular eclipse, the remaining part of the solar surface is too bright to look at safely without taking special precautions.

The region on the earth from which the sun is blocked at a total eclipse is in the shadow of the moon. The moon's shadow is long and tapering, and only barely reaches the earth. For the July 11, 1991, total solar eclipse, the shadow was never more than 160 miles (258 kilometers) across. As the earth rotated and as the shadow moved through space, the shadow swept out a region thousands of miles (kilometers) long. It began in the ocean west of Hawaii, crossed the Big Island of Hawaii and more Pacific Ocean, reached Mexico, and continued through Central America and South America. For thousands of miles (kilometers), to either side, people saw the sun partially covered by the moon, but these partial phases are not spectacular. Thus the coterie of people seeing a total solar eclipse is relatively small.

A lunar eclipse, on the other hand, is visible to people over about half the surface of the earth. They merely have to be able to see the moon at a time when the earth's shadow falls on it. Though it is by no means spectacular, a total lunar eclipse can be beautiful and awe-inspiring as the moon darkens until it is dimly seen as a faint reddish object in the sky. It gets its red color because the small fraction of the sun's light that passes through the earth's atmosphere and strikes the moon is reddish. The earth's atmosphere scatters the blue light better than the red, making the sky blue for other people and leaving only the red to get through. Sunsets are red for the same reason.

It is easy to understand why total eclipses are so memorable in ancient records. The darkening of daytime until the solar corona, the stars, and the planets are visible is so dramatic that even today's observers often regain a tremendous sense of awe. Mark Twain put the idea to memorable use in his novel *A Connecticut Yankee in King Arthur's Court*. His hero supposedly fell asleep and awakened in King Arthur's ancient England. "But all of a sudden I stumbled on the very thing, just by luck. I knew that the only total eclipse of the sun in the first half of the sixth century occurred on the 21st of June, AD 528, OS, and began at 3 minutes after 12 noon. I also knew that no total eclipse of the sun was due in what to *me* was the present year – *i.e.*, 1879. So, if I could keep my anxiety and curiosity from eating the heart out of me for forty-eight hours, I should then find out for certain whether this boy was telling me the truth or not." Fortunately, to save himself, our hero remembered, "It came into my mind, in the nick of time, how Columbus, or Cortez, or one of those people, played an eclipse as a saving trump once, on some savages, and I saw my chance." "Go back and tell the king," our hero said, "that at that hour I will smother the whole world in the dead blackness of midnight; I will blot out the sun, and he shall never shine again; the fruits of the earth shall rot for lack of light and warmth, and the peoples of the earth shall famish and die, to the last man!" Finally, the king gave in and spared our hero, who had to stall until the eclipse was total. "It got to be pitch-dark, at last, and the multitude groaned with horror to feel the cold uncanny night breezes fan through the place and see the stars come out and twinkle in the sky. At last the eclipse was total, and I was very glad of it." Finally, "I said, with the most awful solemnity: 'Let the enchantment dissolve and pass harmless away!' When the silver rim of the sun pushed itself out, a moment or two later, the assemblage broke loose with a vast shout and came pouring down like a deluge to smother me with blessings and gratitude . . . ."

Twain's description of an eclipse is accurate, but eclipses in stories are sometimes not true to life. In H. R. Haggard's famous 1885 story *King Solomon's Mines*, an eclipse is similarly used to gain influence. "Tell them that you will darken the sun to-morrow." I am sympathetic to their worry that "suppose the almanac is wrong." The reply that "Eclipses always come up to time" was surely reassuring. However, the author obviously had never seen a total eclipse, because he allows an hour of darkness for people to sneak away.

Mark Twain's and Haggard's fictions are fun, but a real story was similar. Christopher Columbus, nearly 500 years ago, had actually used a total eclipse of the moon to his own advantage when he was stranded in Jamaica. He knew from the tables of astronomical positions he carried that a lunar eclipse would take place on February 29, 1504. He scheduled a meeting with the local chiefs to take place during the eclipse. He used the eclipse to bargain for a restoration of food deliveries.

The Shawnee Prophet known as Tenskwatawa, who was an important leader of Native Americans in Ohio and Indiana in the early 1800s, used his knowledge of a forthcoming eclipse to solidify his power. When challenged by William Henry Harrison, then governor of the Indiana Territory and later

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to be President of the United States, to "cause the sun to stand still" or some other miracle, Tenskwatawa offered to "blacken the face of the sun." And so he did, or seemed to, though only for the duration of the July 16, 1806, total eclipse.

Farther back in time, people were often surprised by eclipses. The Greek historian Herodotus in 430 BC described how, on May 28, 585 BC, a total eclipse occurred during a lengthy war between the Lydians and the Medes. The Lydians and the Medes quickly reached a peace agreement. Herodotus also wrote that the Greek astronomer Thales had predicted the year of the eclipse. Still, the armies probably did not know what was coming. In any case, as we see from today's supermarket astrology predictions, people are often superstitious even when scientific truth is known.

If we count partial, annular, and total eclipses, as well as all types of lunar eclipses, there can actually be as many as seven eclipses in a given year. But total solar eclipses occur only about every 18 months. If we were to stay in one position on the earth, a total solar eclipse would come to us only about every 330 years. Now that we are a mobile society, it is much easier to travel to eclipses. Tens of thousands of tourists now make it their practice to assemble at places where eclipses will pass. Though often called "eclipse chasers," they are actually the opposite, for eclipses go too fast to chase. The moon's shadow whizzes across the earth's surface at speeds greater than 1,000 miles per hour.

By keeping track of solar and lunar eclipses, ancient peoples were able to figure out intervals by which eclipses repeat. Whether or not the impressive stone pylons erected over 4,000 years ago at Stonehenge, in south England, are used as part of a giant calendar to predict eclipses is controversial. There is little disagreement, however, that the stones of Stonehenge were used to mark the positions in the sky where the sun and the moon reached their extreme locations to the north or south. Thirty years ago the astronomers Gerald Hawkins and Fred Hoyle suggested ways in which a set of holes outside the main ring could be used to mark eclipse cycles. Moving stones from hole to hole at fixed intervals could have kept track of eclipses. Of course, the people at Stonehenge would have seen mainly partial eclipses, and even many of those would have been lost to cloudy weather. Since we have no written records from the time, it is up to each of us to decide whether the Stonehenge erectors really predicted eclipses or whether we are merely smart enough to think of ways that they could have done so.

Much closer to our time, it is clear that the Maya in Mesoamerica knew how to keep track of eclipse cycles and how to predict eclipses. I asked my colleague Sam Edgerton, of the Clark Art Institute in Williamstown, Massachusetts, to tell me about the Mayan records. Sam now often forsakes his former primary field, the study of art in Renaissance Italy and the discoveries made then by Galileo and his contemporaries, for investigations in the jungles of Central America. He explained to me that the Dresden Codex is a

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book of hieroglyphics giving dates from about AD 700 until it was written in about 1400, one of only four that had not been burnt by the conquistadors. The Codex got its name from its current location in Dresden, Germany, where it was noticed in the eighteenth century. It may have been brought to Europe in 1519 by Cortés as a gift to the emperor Charles V after the conquistadors ravaged the Mayan civilization. "In order for them to go from the ground to the stars in this agricultural community, all the metaphors, all the iconography of existence, of life and death, were based on the metaphors of agriculture. They had an idea of things cycling back. The word Maya itself means "people of the cycle."

"The Maya developed a very complex religion, thought, mythology, and a language system that was to communicate this, to keep a record of it. The Maya were concerned that events that happened in historical time repeated themselves. And they should be ready for these, because many of the events were disasters: the coming of floods, the coming of dry seasons, the coming of one terrible consequence or another." Sam went on to explain, "So the Maya took their relationship to the stars and made it a little more scientific in that they organized it around a record-keeping system. Their writing of glyphs and their inventing of an arithmetical system were built in order to keep track of the historical record that they imagined began at a mythological date way back at a time that they fixed. And everything progressed on a date calendar afterward.

"So, getting to why the Maya would keep track of eclipses, it was only one of a number of astronomical events that interested them: the rising and setting of Venus, for example, was very important. Venus was seen as the herald of the sun. As Venus came up and led the sun up, Venus was seen as a dog, literally, leading his master up and taking his master down into the underworld.

"The Dresden Codex was one of a number on bark paper. They folded it like an accordion. This one was about 20 feet long. They would keep track, for example, of the vernal equinox, which was very important because then you would tell the farmers to start planting.

"The Dresden Codex is, in fact, an almanac used to predict the rise and fall of Venus and of eclipses. But," he explained, "it's not an eclipse record as such, but a record of times when eclipses *can* happen."

Sam showed me how the glyphs give the number of days in the intervals between eclipses. "In a large Mayan number like this, the bottom row has 3 bars, which is 15, and the two dots make 17. The bar on the top with three dots makes 8. In the top row, you multiply by twenty, just as you know that in the decimal system that 1. is 10 times greater than .1; twenty times 8 is 160, plus 17 makes 177. Sometimes the top shows 7, and twenty times 7 is 140, plus 18 in the bottom row makes 148." We now know that these intervals of 177 days and 148 days occur because they correspond to when the sun and moon are at the positions in their orbits where the orbits apparently cross as seen from earth. Indeed, these intervals also describe eclipses of our own times. We say that they link "eclipse seasons." The next total eclipse after July 11, 1991, took place about twice 177 days later, on June 30, 1992. There will be an interval of 177 days between the May 10, 1994, annular eclipse and the November 3, 1994, total solar eclipse.

But the Mayan eclipse dates give merely the times when eclipses were possible, not when they would actually occur. So they would tell the people when to be ready for eclipses, but were not actual predictions. Still, if the Arawak Indians who met Columbus in Jamaica had been Maya, they might have known almost as much about predicting eclipses as Columbus did.

Sam also explained the glyphs to the left of the page. "Below the sky bar in the middle, we see dark and light bands. The fact that you have the dark band and the light band shows that you are confused by the sun and the moon. Now, right below that, you see the same sky bar with the Venus symbol on the left. The two black and white things with the crossed bones. Notice that underneath that is the serpent with an open mouth. That is the image of the earth, the earth serpent, like a celestial monster. From the sky bar, down descends the black/white, meaning the sun and the moon, and it's about to be swallowed up by the earth's serpent."

Within every 18-year interval, we have a series of solar eclipses, some long and some short. The longest eclipse ever possible has 7 minutes 31 seconds of totality. The June 30, 1973, eclipse that crossed Africa was the only eclipse this century to exceed 7 minutes. One saros later, after waiting 18 years 11⅓ days, we had the long eclipse of July 11, 1991, whose longest totality was just under 7 minutes. This long eclipse in the saros won't repeat until July 22, 2009.

The last few years have been very exciting for studies of the sun, because the amount of solar activity was at a near-record high. The easiest way to see the solar activity is by observing sunspots, which wax and wane in number with a period of about 11 years. The peak of this sunspot cycle, the second highest ever recorded since sunspots were discovered by Galileo in 1610, occurred in July 1989. But solar activity continues to be high for a couple of years after the sunspot peak, and powerful flares more often occur in this post-maximum period. The spring of 1991 saw the earth bombarded with particles and radiation from a series of powerful flares on the sun. They caused the aurorae to be seen more widely than usual, and threatened power lines with surges of current. The sunspot number declined rapidly in 1992, as we approach the 1995 sunspot minimum.

The corona is but one of the solar phenomena that changes with the solar-activity cycle. At solar minimum, when the number of sunspots we see is close to zero, the corona extends mainly outward from the sun's equator. The sun's magnetic field binds the coronal gas into beautiful shapes called streamers. Some are wide at their base and curve down into points; they resemble ancient helmets, and so are called "helmet streamers." At the sun's poles, thinner streams of gas can be seen following the sun's magnetic field, like iron filings following the magnetic field of a bar magnet.

As solar activity increases, the number of streamers increases and they appear at a wider range of solar latitudes. When we see them in projection, as three-dimensional spikes projected against the sky, the streamers then make the solar corona appear round. Thus the round corona at the 1980 eclipse contrasted with the irregularly shaped corona at the 1984 eclipse. The presence of the solar-activity maximum made the 1991 eclipse especially interesting. Often, there were a hundred or more sunspots on the face of the sun, and the corona was very round. We will be back near the peak of the sunspot cycle for the 1999 eclipse, which crosses Europe.

Further, the decade of the 1980s had been one of tremendous technological advance. Instead of film, for which only about one out of every 100 photons of light that hits contributes to the image, astronomers mainly now use electronic imagers that sense about half the photons. Thus our cameras – using these new "charge-coupled devices," or CCDs – are about 50 times more sensitive. In one sense, in four minutes of total eclipse, we can do 4 times 50, or 200 times, the observations we could do ten years ago. It is like having a 200 minute, or 3 hour 20 minute, eclipse. We (JMP and students and colleagues) could thus plan to make a map of the temperature of the corona whereas ten years ago, with the same method, we could have merely determined the temperature at one or two points. A grant from the Committee on Research and Exploration of the National Geographic Society aided us in making our expedition.

Another major advance in astronomy in the past decade was the development of devices that could sense the infrared part of the spectrum far better than before. These infrared devices could not map as finely as CCDs, but they were still far better than observing point by point. The 1991 eclipse, astonishingly, linked the development of these new infrared imagers with the ability to observe the infrared, which does not come down to ground level. The eclipse, fortunately, passed directly over the top of Mauna Kea, where more of the world's largest telescopes exist than at any other location. Only every few decades does a total eclipse pass over a modern major observatory. For some of the infrared-imaging experiments, it wasn't even necessary to use the big telescopes, since the sun is so bright compared with the stars and nebulae usually observed. We discuss this magnificent eclipse in Chapter 8.

Advances in theory also called for making maximum use of the long total eclipse. Since observations from a spacecraft showed 15 years ago that our old ideas were wrong about how the solar corona was heated, new models have been developed. We now think that the sun's magnetic field is important in channeling special kinds of waves from under the sun's