Chapter 16

Venus Tries to Cover Immodestly

In This Chapter

- Measuring the solar system is hard
- Transits of Venus took us to the south seas
- Transits of Mercury are practice
- We get a chance soon

Total solar eclipses, when the Moon goes in front of the Sun and blocks its light entirely, are rare. Yet if you travel, you can see one every year and a half or so. One astronomical phenomenon comes around with a much longer interval of over 100 years. This event is a transit of Venus, a passage of Venus across the face of the Sun. Nobody alive has ever seen one, yet two are coming up in the next decade. What an opportunity!

A Blot on the Face of the Sun

On November 24, 1639 O.S., 20-year-old Englishman Jeremiah Horrocks searched for a transit of Venus. Kepler, who had predicted the 1631 transit, didn't predict this one, but Horrocks had re-evaluated Kepler's calculations. He started observing early, in case the predictions were off. When some clouds cleared up, he clearly saw a circular black spot silhouetted against the Sun. He had alerted a friend some miles away, who got a glimpse of this circular black shape through a hole in the clouds that briefly opened at his site. Could it have been a sunspot that Horrocks saw?

But what he had seen was even rarer. The black spot was Venus silhouetted against the Sun. Though Venus is larger than the Moon, it is much farther away and, therefore, takes up a much smaller angle on the sky. So rather than blocking out the Sun, it merely shows as a spot only about 3 percent the Sun's diameter. Unless you were observing the Sun, you wouldn't notice it.

Sun Safety

Horrocks was observing the Sun by projecting its light onto a screen. Remember that you should never stare at the Sun directly without special filters. Special filters or projection are needed to observe transits of Venus or of any other object that is not fully blocking the everyday solar surface.

The Solar Scoop

Dates given in Old Style (O.S.) are from before the calendar reform that took 10 days off the schedule, making the Gregorian calendar we use today. On the European continent, the change was made in 1582. But in England, where Horrocks was observing, and its American colonies, the change didn't take place until 1752. So the date of the 1639 transit was recorded differently depending on location.

After Edmond Halley figured out that a certain apparent set of comets was really one single comet returning periodically—an object that we now call by his name—he turned his attention to other topics. Earlier, at the age of 21, he had observed a transit of Mercury while on the isolated mid-Atlantic island of St. Helena to make a southern star catalogue. Much later, in 1716, Halley figured out that transits of Venus could be the way to solve one of the major problems of astronomy: How big is the solar system? At the time, the average distance of the Sun from Earth, which is known as the astronomical unit, was known to an accuracy of only about 20 percent—that is, it was somewhere between 135 million km and 165 million km (about 80 million miles and 110 million miles). In 1720, Halley became Astronomer Royal.

In Chapter 4, you learned how Johannes Kepler figured out the basic laws of how planets moved around the Sun. His first two laws were part of his book *Astronomia Nova* (*The New Astronomy*), published in 1609. His first law states that the planets orbit the Sun in ellipses, with the Sun at one focus of each ellipse. His second law states that if you draw a line connecting a planet with the Sun, in each time interval of a certain duration, that line sweeps out an area that is always the same. This law implies that when a planet is relatively close to the Sun, it moves faster in its orbit, since the triangle that the line sweeps out has to be wide and squat compared with the narrow, tall triangle swept out at other times. In 1618, in Kepler's book *Harmonices Mundi* (*On the Harmony of the World*), he advanced his third law: The period of a planet's orbit cubed is equal to the size of its orbit squared, when given in units of Earth's orbit.

Sun Words

A **transit** is a passage of an astronomical body in front of another. An object passing in front of the Sun is called a transit of that object. A solar eclipse, indeed, is a type of transit, one involving the Moon. Only two other objects of substantial size in our solar system transit the Sun: the planets Mercury and Venus, whose orbits are within Earth's. Astronomers can now pick up exoplanets—planets that orbit other stars—transiting in front of their stars.

All Kepler's relationships were relative: Jupiter's orbit is 5.2 times bigger than Earth's, and its period is 10 times longer. But nowhere in Kepler's laws does it say how big Earth's orbit is or how big Jupiter's orbit is in actual units of length, such as kilometers or miles.

Halley had the brilliant idea of using a transit of Venus to compute the actual size of the solar system. By the time he thought of it, he knew that the next transits of Venus would be only a few decades away, in 1761 and 1769. Halley realized that if people looked at the transit from different locations on Earth, the line from each telescope to Venus and onward would hit the Sun at a slightly different place. The farther Venus is from the Earth, the smaller the deviation of the position at the Sun would be. By timing accurately how long Venus would take to cross the Sun, scientists could later calculate how far away Venus was.

With the prospect in mind of solving the problem of the size of the solar system, many nations equipped and sent out scientific expeditions to the 1761 and 1769 transits. To apply Halley's method, it was important to have the expeditions spaced as widely as possible across the face of the Earth.

Solar Scribblings

English surveyors Charles Mason and Jeremiah Dixon were sent by their government to Sumatra to observe the 1761 transit, but their ship was attacked by the French before they got too far. After returning home with their dead and wounded and repairing the ship, they made it as far as Cape Town, South Africa. Their results were so good that they were next dispatched to the American colonies to survey the disputed Pennsylvania-Maryland border. The result was the Mason-Dixon line.

For the 1769 transit, the British Admiralty, which administered the world's greatest sea power, appointed a young lieutenant, James Cook, as captain of its ship, the *Endeavour*. Captain Cook was sent to Tahiti, in the South Pacific, to observe the transit; he took with him astronomer Charles Green. Of course, Captain Cook became one of the most famous sailors of all time from this expedition, which went on to sight Australia and the islands of New Zealand for the first time for Europeans. There had been rumors of a "Great Southern Continent," and Captain Cook went on to find out what he could about it. As a result, I like to consider the European colonization of Australia and New Zealand a spin-off of astronomy.

The results of the various expeditions gave distances for the astronomical unit that ranged from 93 million to 97 million miles, an uncertainty of about 2 percent around a central value of 95 million miles. We know now that the actual value—92,957,000 miles— is at the bottom of the range.

Good Things Come in Pairs

Transits of Venus may be very rare, but they come in pairs. Each pair is separated by only eight years. But then there is a gap of over 100 years until the next pair.

Just as eclipses of the Sun occur only when the Sun, the Moon, and Earth are in line, transits of Venus occur only when the Sun, Venus, and Earth are in line. When that happens depends on the orientations and tilts of the planets' orbits around the Sun. Note from the following list that these nodes in the orbit occur only in June or December. The gap alternates between about 105 years and about 122 years.

Transits of Venus:

- 1631: December 7 (unobserved)

  1639: December 4 (November 24 O.S.)
- 1761: June 6 (after a gap of nearly 122 years)

  1769: June 3–4
- 1874: December 8–9 (after a gap of 105 years)

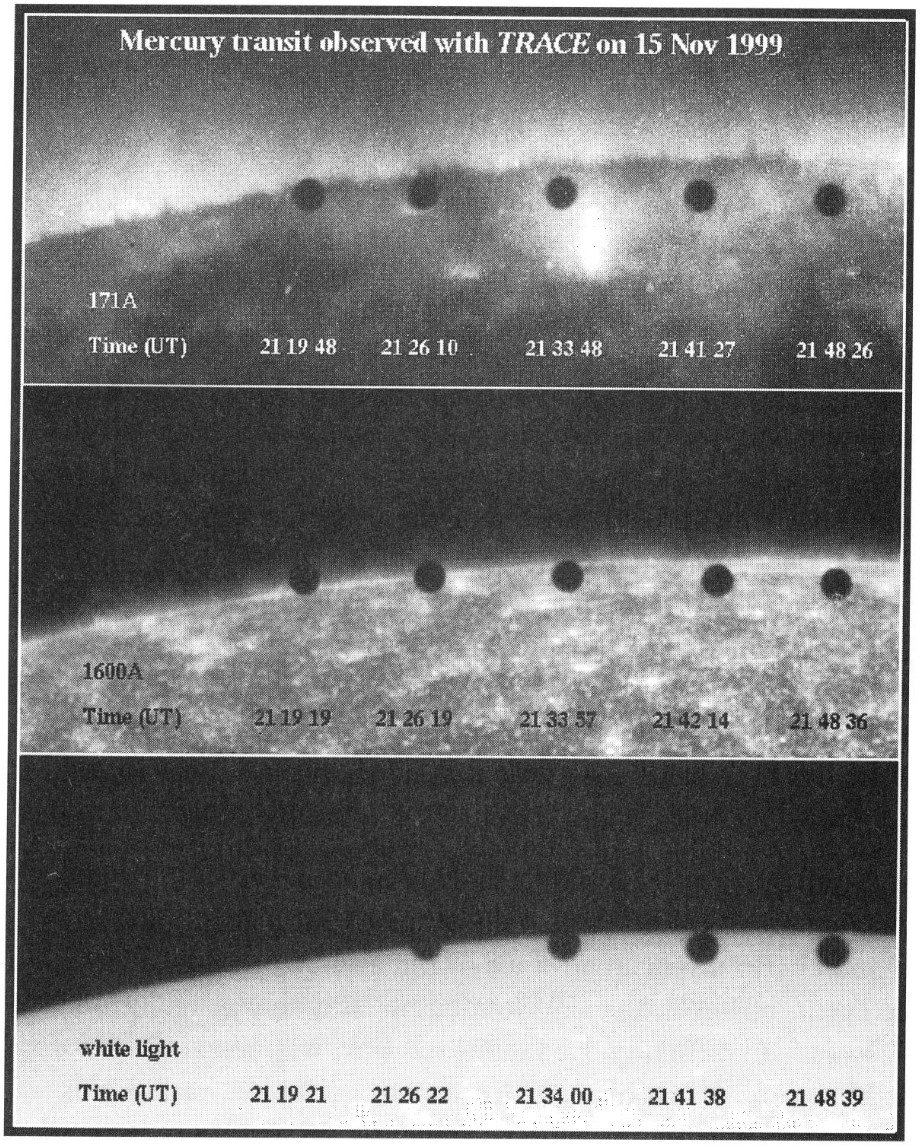
  1882: December 6
- 2004: June 8 (after a gap of nearly 122 years)

  2012: June 5–6
- 2117: December 11 (after a gap of 105 years)

  2125: December 8

The Black-Drop Effect

Timing the transit required accurate clocks. The best clocks of that time used pendulums to beat steady time and had to be set up on firm surfaces, not on the desks of ships on the rolling seas. In her best-selling book *Longitude*, Dava Sobel beautifully described the trials that her hero went through to get his spring-wound clocks accepted.



The 1999 transit of Mercury observed with the Transition Region and Coronal Explorer (TRACE) spacecraft. The image at 171 A is from million-degree iron (8-times ionized); the image at 1600 A is taken of continuous radiation from chromospheric heights, and the white light image shows Mercury silhouetted against the photosphere.

But even with a decent clock, a completely unexpected problem appeared: It was not possible to accurately measure the instant when Venus became fully silhouetted against the Sun. It had been thought that you would merely see Venus's disk touching the edge of the Sun. But instead, as Venus moved entirely in the Sun, a black band—curved on each side—seemed to join Venus with the outside sky. The band seemed

Sun Words

The **black-drop effect** is the appearance of a dark band joining Venus's silhouette and the sky, preventing accurate timing of the transit.

like a black drop of fluid coming in from the edge of the Sun, and the effect became called the *black-drop effect.* The band pulled out, like taffy, and eventually snapped, showing Venus fully silhouetted. But 10 seconds or so of uncertainty had ensued. That uncertainty in time by an unexpected factor of 5 translated to an uncertainty increased by the same factor of 5 in the distance of Venus from Earth.

Lengthy Expeditions

In the twenty-first century, you can fly off to Antarctica, see a solar eclipse, and be home in a week. In the early twentieth century, an eclipse expedition to Russia in 1936 involved many weeks in a chartered train to take the equipment and crew out to Siberia. But these travails pale in insignificance next to the effort necessary for eighteenth-century expeditions to transits of Venus.

One of the leading scientists in the field was Guillaume Joseph Hyacinthe Jean Baptiste le Gentil de la Galasière of France. Le Gentil had carried out some of the fundamental analyses of the theory, extending Halley's work. For the transit of 1761, he set out in a French vessel to Pondicherry, a French possession in India. The French were at war with the English, who controlled the seas in general, in addition to making a specific siege of Pondicherry. He managed to obtain a letter guaranteeing him safe passage. Weeks later, he was prevented from landing in India because of the fighting. He could observe the transit, which took place in clear skies, only from the ship. The rocking of the ship meant that his clock wasn't accurate. Thus, he could not make the measurements that he needed.

Le Gentil decided to wait for the transit of 1769, which was, after all, "only" eight years later. This time, he was almost arrested as a spy at his choice site in Manila, but he managed to get to Pondicherry a year in advance of the event to set up his equipment. Hours before the event, however, the sky clouded up, and he was again foiled. His trip home rivaled Ulysses's in difficulty. Le Gentil fell sick, was hospitalized for some months, and was shipwrecked. It took years for him to get home, making his total absence 11 years and 6 months. By the time he returned, he had been declared dead and his estate had been divided up among his heirs. His seat in the French Academy, the high academic honor, had been given away. His personal story eventually ended happily, after years of misery.

The expeditions may have been difficult, but the data were valuable. The results published two years after the second transit of the pair found 153 ± 1 million km for the size of the astronomical unit. A later analysis, by the famed nineteenth-century American astronomer Simon Newcomb, used better methods with the same data to find 149.59 million kilometers. Today's value, measured to within meters using radar and adopted as the official value of the astronomical unit by the International Astronomical Union, is 149,597,870 km.

Solar Scribblings

The story of Le Gentil's expeditions has been told in a 1990s play, *The Transit of Venus*, by the Canadian playwright Maureen Hunter.

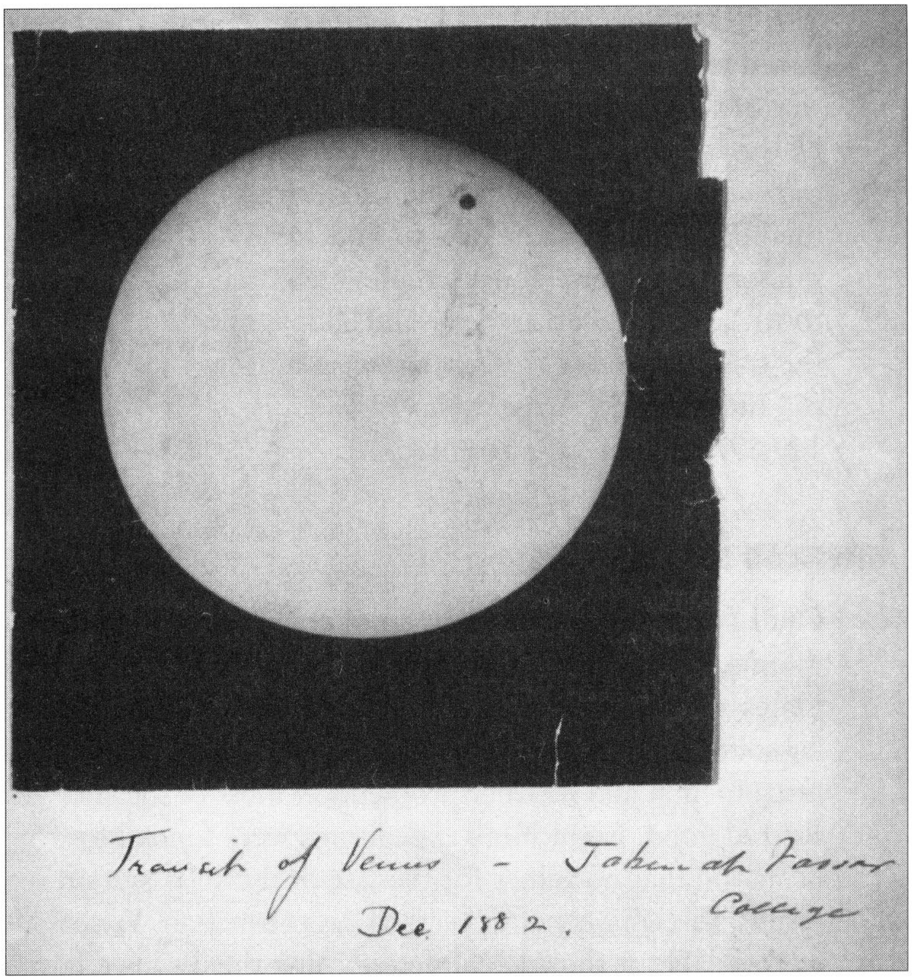
American Expeditions

Out of dozens of expeditions from countries around the world, eight American expeditions, funded by Congress, went to the 1874 transit of Venus, some in the United States and others abroad. Observation sites for the event were all over the world, as far south as Tasmania and New Zealand and as far north as Siberia. But there were instrumental and weather problems at most of the sites, and the results were not considered good. Eight more expeditions were funded for the 1882 event. Though it has been said that no values for the size of the solar system resulted, there actually were results, though only after years of data reduction. When put together with other methods available at the time of determining the distance to the Sun, the results were not heavily weighted. By this time, observations from distant locations of Mars and of asteroids gave reasonably good values for the astronomical unit.

One of the best-known American observers of the 1882 transit was Maria Mitchell, who had gained fame as a girl when she discovered a comet, for which she had won a gold medal from the King of Denmark. At the time of the transit, Mitchell was a professor of astronomy at Vassar College in Poughkeepsie, New York. She and her students observed the transit from the College Observatory. The photographs Mitchell took of the transits of 1874 and 1882 are an important part of the early history of astronomical photography.

Solar Scribblings

Mary Lyon, founder of the Mt. Holyoke Seminary for Women (now Mount Holyoke College) in South Hadley, Massachusetts, sent two teachers to South Africa in the mid-nineteenth century to found a seminary there. Mt. Holyoke also transferred its 1853 telescope to the South African seminary in time for it to be used to observe the 1882 transit of Venus.



The 1882 transit of Venus, photographed by Maria Mitchell and her students at Vassar College.

(Special Collections, Vassar College Libraries)

Not Venus's Atmosphere

When Venus is near to the Sun in the sky but is not silhouetted against it, a bright ring around Venus has been observed. The effect is that of Venus's atmosphere refracting (bending) sunlight toward us. In the second half of the twentieth century, Venus's atmosphere was explored by spacecraft that flew by, orbited, or even landed on the planet. Venus has a thick, dense, atmosphere, with cloud cover so heavy that we cannot see through to the exceedingly hot and unpleasant surface.

Because Venus's atmosphere is so well known, many, if not most, people have assumed that the black-drop effect is caused by Venus's atmosphere. But the atmosphere is not even close to thick enough to create an effect the size of the black drop. Still, many books and articles persist with this incorrect explanation.

Mercury to the Rescue

Though at the time of a transit Venus is as close as a planet ever can be to Earth, the planet Mercury also transits the Sun and can be used to measure the Sun's distance. Mercury is smaller than Venus and also over twice as far away, so its silhouette against the Sun is even smaller than Venus's. Mercury is only about half of 1 percent of the size of the Sun in angle in the sky: 10 arc seconds compared with 30 arc minutes (30 × 60 = 1,800 arc seconds).

A transit of Mercury was observed historically even before a transit of Venus. French astronomer Pierre Gassendi saw the Mercury transit of November 6, 1631, which had been predicted by Kepler on the basis of the *Rudolphine Tables* he had compiled.

Sun Safety

As with transits of Venus, you must use special filters or projection methods to view transits of Mercury, since the everyday surface of the Sun is visible throughout.

Mercury's transits are at least 10 times more common than Venus's. There are about a dozen per century, but because Mercury's orbit is tilted 7° with respect to Earth's, only about one out of two dozen of Mercury's orbits lead to a transit. Each transit lasts about five hours. The beginning of the November 8, 2006, transit of Mercury will be visible from all of the western hemisphere.

The next table illustrates how transits of Mercury, like transits of Venus, occur in pairs. In both cases, the pairs represent opposite nodes of the orbits. Transits of Mercury occur only in May and November.

Transits of Mercury:

- 1993: November 6 (corona only)

  1999: November 15

- 2003: May 7

  2006: November 8–9

- 2016: May 9

  2019: November 11

- 2032: November 13

  2039: November 7

Solar Scribblings

The beginning of the November 8, 2006, transit will be visible in the afternoon from all of North and South America. Hawaii, but not the rest of the United States, will be well placed for midtransit. The end of the transit will be visible from all of Australia, but only from the extreme east coast of Asia.

The transit will last from 19:13 U.T. to 00:11 U.T., with midtransit at 21:42 U.T. (U.T. is Universal Time, which basically corresponds to British time, five hours later than Eastern Standard Time and eight hours later than Pacific Standard Time.) Thus, the transit starts at 2:13 P.M. E.S.T. on the East Coast and 11:13 E.S.T. on the West Coast. The Sun will set with Mercury still transiting.

Most transits of Mercury have been observed only with ground-based telescopes. But telescopes in orbit to observe the Sun have observed the transits of Mercury of 1993 and 1999. The 1993 transit was observed by the Japanese x-ray telescope known as Yohkoh (Sunbeam), using an American-built camera aboard. Indeed, Mercury crossed in front of the solar corona, which was continuously visible from the spacecraft but which is not generally visible from Earth; this transit does not appear in ordinary tables of transits of Mercury.

The 1999 transit was observed with the Transition Region and Coronal Explorer, known as TRACE, a NASA spacecraft built by the groups of Alan Title at Lockheed Martin's space sciences laboratory and Leon Golub at the Harvard-Smithsonian Center for Astrophysics. I spent a sabbatical year in which I worked with Golub, and my appreciation of the problem of the black-drop effect was enhanced through a historical paper delivered at an American Astronomical Society meeting by Brad Schaefer, then at Yale and now at the University of Texas at Austin. He pointed out that most of the sources he examined, both books and scientific articles, mistakenly claimed that the black-drop effect was caused by Venus's atmosphere.

I brought the suggestion of examining the TRACE transit of Mercury to Glenn Schneider, a scientist at the Lunar and Planetary Laboratory at the University of Arizona who works intensively with one of the cameras on the Hubble Space Telescope. Golub, Schneider, and I presented a paper with our results at a meeting of the Division of Planetary Sciences of the American Astronomical Society, held in New Orleans.

Perhaps a surprise was that even the transit of Mercury observed from TRACE still showed a black-drop effect. After all, Mercury has no atmosphere (or, at least, a completely negligible one). Furthermore, TRACE was observing from outside Earth's atmosphere, so we knew that Earth's atmosphere was not contributing to this particular black-drop effect.

By modeling the effects in a computer, we reported that the black-drop effect observed for Mercury came from two sources:

- The instrument involved a small telescope, which had its own fundamental limitation to the clarity of its view. The resulting blurring contributed.
- The Sun shades off in darkness near its edge.

The blurring from the instrument compounded with the darkening near the Sun's edge provided all the observed black drop, even without any atmosphere on Mercury.

What is this darkening near the Sun's edge? It is known as limb darkening, since the edges of the Sun and stars are known as their limbs. We see into the Sun until its gas gets too murky for us to see farther. When we look at the center of the Sun's disk, we see in as far as a certain level that we call the Sun's surface. When we look near the limb, though, we are looking diagonally. The murkiness adds up so that we can't see any farther at a point that is above the Sun's surface. Then we see a brightness that corresponds to the temperature of the gas at that point and regions near it. From the fact that the points near the edge look darker than the points at the center of the Sun's disk, we deduce that they are cooler. We know this since cooler gas is not as bright as hotter gas.

Thus, we have shown the black-drop effect for a transit of Mercury to arise from the instrumental blurring plus the Sun's limb darkening. A transit of Venus must have the same contributing factors. For observations of transits of Mercury or Venus from Earth, the blurring from Earth's atmosphere can contribute as well. But Venus's atmosphere is not sufficiently thick in size to contribute substantially.

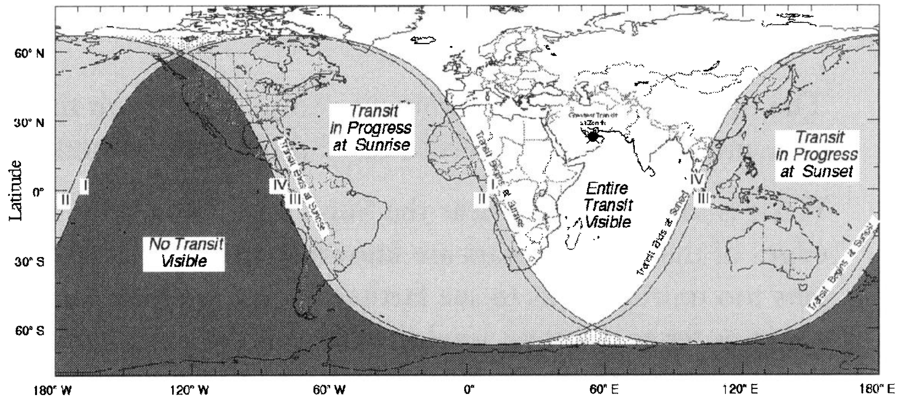
Our Time Has Come

Our generation on Earth will be fortunate to see transits of Venus, even though nobody now alive has ever seen one. The oldest people on Earth are about 115 years old, according to *Guinness World Records*, and it will have been a 122-year gap.

The Transit of 2004

On June 8, 2004, the beginning of the transit will be visible from a large part of the world, from the Middle East eastward through all of Asia. The transit will take about six hours. The Sun will rise with the transit already begun for the eastern part of the United States and Canada, as well as the eastern part of South America and the western part of Africa. The Sun will set with the transit going on for people on the west coast of China and Japan, and people in the South Pacific, including Indonesia and Australia.

In between, including essentially all of Europe and Asia, the whole six hours of transit will be visible. Weather predictions based on past statistics of clear sky show that sites in Egypt may be especially favored, though the event will be high in the sky throughout the entire Middle East across as far as India.

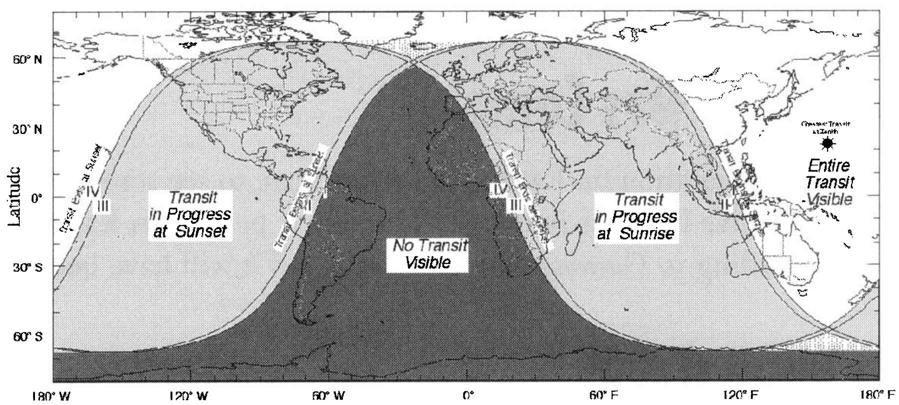


The transit of Venus of 2004.

(F. Espenak, NASA's GSFC)

The Transit of 2012

The circumstances on Earth for 2012 will be almost the opposite of those for the 2004 event. The transit will have begun as the sun rises in almost all of Europe and in Asia as far as mid-China and Indonesia. From mid-Australia and mid-China and Russia, through Japan, and past Alaska, the entire transit will be visible. The Sun will set while the transit is going on throughout the rest of the United States, including Hawaii and the whole mainland, also including Mexico and Central America.



The transit of Venus of 2012.

(F. Espenak, NASA's GSFC)

The transits of Venus won't be as spectacular to the eye as total eclipses of the Sun. Nevertheless, as intellectually and historically interesting events, they will rank very high.

Solar Scribblings

As we go out into the solar system with robotic and crewed spacecraft, we will have chances to see other objects transit the Sun. From Mars, one of its two moons, Phobos and Deimos, will transit every week or so. From Jupiter, five of its satellites will hide the Sun entirely. Remember that Jupiter is five times farther from the Sun than Earth is, so the Sun appears five times smaller than it does from Earth. From Saturn, the Sun appears 10 times smaller than it does from Earth, and four of its satellites entirely hide the Sun; transits of others will be observable. The transit of Earth as seen from Saturn on January 13, 2005, will be difficult to detect even for the Cassini spacecraft that will then be in orbit around it. And Cassini is not allowed to be pointed toward the Sun. The Sun appears so small from Uranus, Neptune, and Pluto that transits by most of their moons would be total eclipses.

The Least You Need to Know

- Halley and others calculated how transits of Venus could be used to measure the size of the solar system.
- Eighteenth-century expeditions were many, but their success was limited by the black-drop effect.
- Modern studies of transits of Mercury have shown that the black-drop effect results from the darkening of the Sun near its edge and from the limited resolution of telescopes.
- The transits of 2004 and 2012 will be contemporary chances to repeat historical accomplishments.