

The Transit of Venus

When Venus crosses
the face of the sun
this June, scientists
will celebrate one
of the greatest stories
in the history of astronomy

By Steven J. Dick

“We are now on the eve of the second transit of a pair, after which there will be no other till the




BLACK DOT in front of the sun is Venus, photographed during the last transit in 1882.

twenty-first century of our era has dawned upon the earth, and the June flowers are blooming in 2004.... What will be the state

of science when the next transit season arrives God only knows.”

—U.S. Naval Observatory astronomer

William Harkness, 1882



June 8, 2004, will dawn just like any other day, but around the world many lucky individuals will witness an extraordinarily rare astronomical event. Properly situated observers equipped with suitable filters

for their eyes, binoculars or telescopes will be able to see the planet Venus silhouetted against the sun, a black dot moving across the fiery disk for almost six hours. The entire transit of Venus will be visible in most of Asia, Africa and Europe. People in Australia will see only the opening stages of the transit before the sun sets there, and Venus will be three quarters through its crossing by the time the sun rises over the eastern coasts of the U.S. and South America. Those unlucky souls on the western coast of the U.S. and in southwestern South America will miss the event completely [see illustration on page 104].

A transit of Venus is not nearly as spectacular as a solar eclipse, caused by the passage of the moon between Earth and the sun. Although Venus is three and a half times as large as the moon, it is so much farther away from Earth that it appears as a speck against the sun, with only about 3 percent of the sun's diameter. So why are scientists, educators and amateur astronomers so excited about the upcoming transit? Partly because it is such a rare phenomenon—astronomers have observed a transit of Venus only five times before, with the last one occurring on December 6, 1882. If sky watchers miss the 2004 transit, they will have another chance in 2012, but after that they will have to pass the baton to their descendants in the year 2117.

Another part of the transit's appeal is the colorful history of the efforts to observe it in the 17th, 18th and 19th centuries. The story has all the ingredients of a scientific thriller: international rivalry, mysterious observational effects and controversial results bearing on one of the most confounding problems in the history of astronomy. In addition, the phenomenon is of great interest to current researchers because the transit of Venus may shed light on a hot topic in modern astronomy: the detection of planets in other solar systems.

From Kepler to Captain Cook

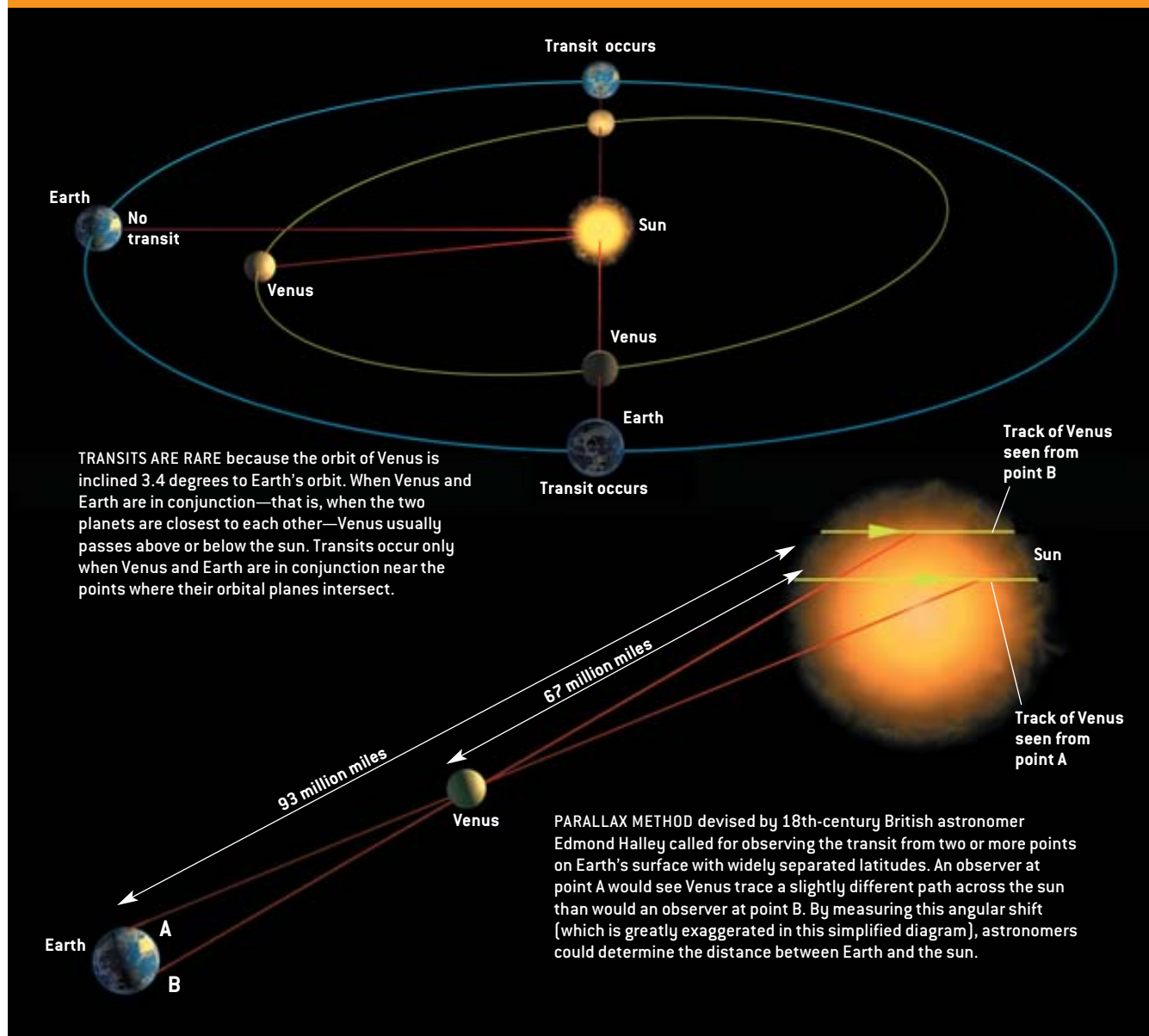
THE OCCURRENCE OF any planetary transit is a simple matter of geometry—the planet in question must pass between the observer and the sun. From Earth, one may see transits of Mercury and Venus. From Mars, one may view a transit of Earth as well. (Arthur C. Clarke's famous short story "Transit of Earth" was inspired by the realization that an observer on Mars on May 11, 1984, would have seen Earth cross the face of the sun.) Such events are relatively rare because the orbits of the planets are not in the same plane as the ecliptic, the sun's path in the sky as seen from Earth. The orbit of Venus, for example, is inclined 3.4 degrees to Earth's orbit, so even when Venus is in the same direction as the sun ("in conjunction," as astronomers say), most of the time it is too far above or below the ecliptic to cross the sun's face [see top illustration in box on opposite page]. For a similar reason, the moon does not eclipse the sun once a month as it orbits Earth; it generally passes above or below the ecliptic.

A transit of Venus takes place only when Earth and Venus are in conjunction near the points where their two orbital planes intersect. As a result, transits typically recur only four times every 243 years. The intervals between transits follow a predictable pattern: one transit is generally followed by another eight years later; the next transit occurs after 105.5 years and the next after another eight years; and the cycle begins again after another 121.5 years. Why do the transits usually occur in pairs separated by eight years? Because Venus takes 224.7 days to travel around the sun, 13 Venusian years are almost exactly equal to eight Earth years. Eight years after the first transit of a pair, Venus and Earth return to almost the same positions in their orbital dance, so they will still be aligned roughly with the sun. The sun's angular diameter—how big it appears in the sky—is about half a degree, which allows a little leeway; if the first

Overview/A Wondrous Transit

- A transit of Venus occurs when the planet passes directly in front of the sun (as observed from Earth). Usually only four transits happen every 243 years.
- Because a transit of Venus is barely visible to the naked eye, astronomers have observed the phenomenon only five times before. In the 18th and 19th centuries, scientists tried to use the transit to gauge the distance between Earth and the sun.
- Professional and amateur astronomers are eagerly awaiting this year's transit. The observations could be useful to researchers who are preparing a spacecraft designed to detect planets in other solar systems.

THE GEOMETRY OF TRANSIT



transit took place near one edge of the solar limb, the next one will be close to the opposite edge. Occasionally, though, only a single transit occurs because one of the pair is a near miss. There was just one transit of Venus in the 14th century, and this will be the case again on December 18, 3089.

Because a transit of Venus is barely visible to the naked eye, for most of history humans went about their lives oblivious to such events. The first to predict a planetary transit was 17th-century German astronomer Johannes Kepler, whose Rudolphine Tables provided what was then the most accurate guide to planetary motion. Kepler determined that Mercury would cross the sun on November 7, 1631, followed by Venus on December 6 of the same year. Kepler did not live to see if his predictions were correct; he died in 1630. But the transit of Mercury was observed by at least three people, most notably French natural philosopher Pierre Gassendi, who left a detailed account. Gassendi estimated

Mercury's apparent diameter to be about 20 arc seconds—that is, about $\frac{1}{180}$ of a degree—which was in itself a considerable scientific advance. The transit of Venus, on the other hand, was not visible in Europe, and although Kepler had spread the word around the world, no one is known to have observed it.

English astronomer Jeremiah Horrocks (1618–1641) realized that another transit of Venus would occur on December 4, 1639. (Horrocks listed the date as November 24 because England did not adopt the Gregorian calendar until 1752.) He set up a small telescope in his home in Much Hoole, near Liverpool; by projecting the light from the telescope onto a sheet of paper, he was able to view an enlarged image of the sun. He saw nothing unusual until noon, when he reluctantly had to dash off, possibly to attend a church service. When he returned shortly after three o'clock, he found Venus already on the face of the sun! Although Horrocks was only able to observe the early stages of the



“I then beheld a most agreeable spectacle ... a spot of **unusual magnitude** and of a **perfectly circular shape**....”
—English astronomer Jeremiah Horrocks, 1639

transit for about 30 minutes before sunset, he estimated Venus’s apparent diameter at about one arc minute, three times the diameter Gassendi had measured for Mercury. From Manchester, 25 miles southeast of Much Hoole, Horrocks’s friend William Crabtree used a similar telescope to glimpse Venus in transit just before sunset. As far as we know, Horrocks and Crabtree were the only two humans to witness the event.

The 1761 and 1769 transits of Venus were the subject of much more serious observations. By this time British Astronomer Royal Edmond Halley, best known for his famous comet, had detailed a method of using the transit of Venus to determine the distance between Earth and the sun (now known as the astronomical unit). If scientists observed the transit from two or more points on Earth’s surface with widely separated latitudes, each observer would see Venus trace a slightly different path across the sun [see bottom illustration in box on preceding page]. Because each path takes the form of a chord—a straight line connecting two points at the edge of the sun’s disk—astronomers could measure the angular shift between the paths by comparing the durations of the transits. This angular shift, called the parallax of Venus, would provide a measure of the distance between Earth and Venus because the two quantities are inversely proportional to each other. To see how this method works, hold a finger in front of your face and view it alternately with one eye and then the other. The apparent shift in the finger’s position as you open and close your eyes is greater when the finger is close to your face than when it is far away.

Although Mercury has 13 or 14 transits every century, it was not a suitable candidate for either Halley’s parallax method or the variations devised by later astronomers. Because Mercury is so far from Earth, the angular shifts were too small to be measured accurately. Even with the much closer Venus, the observations were tricky; it was crucial to know the exact geographic positions of the observing stations and to accurately time the four “contacts” between Venus and the sun. (The first and second contacts occur at ingress, when Venus’s disk touches the sun’s from first the outside and then the inside; the third and fourth contacts occur at egress.) But the potential payoff from the observations would be enormous. Astronomers already knew from Kepler’s laws of planetary motion the relative distances of all the planets from the sun, so they could determine the solar parallax from the parallax of Venus. And this measurement, in turn, would allow scientists to estimate not only the distance between Earth and the sun but also the scale of the entire solar system.

Unfortunately, the results from the 1761 transit were not as good as expected: the measured values of the solar parallax ranged from 8.3 to 10.6 arc seconds. But the observations in 1769 yielded a narrower range—from 8.43 to 8.8 arc seconds—which put the estimate of the astronomical unit between about 93 million and 97 million miles. Among the observers in 1769 was David Rittenhouse, the preeminent scientist in the American colonies, who fainted from excitement after peering through his telescope. The first voyage of British explorer Captain James Cook on the *Endeavour* was mounted in large part to observe the transit while exploring the South Pacific. Cook and his crew did so successfully from an area still known as Point Venus in Tahiti and from two nearby locations. But Cook reported an ominous problem that also plagued other observers: attempts to determine the exact times of contact of Venus with the sun were frustrated because the limbs of the two bodies appeared to cling together for several seconds [see right illustration on opposite page]. Cook speculated that this phenomenon, which became known as the black-drop effect, was caused by “an atmosphere or dusky cloud round the body of the planet.”

When in 1824 German astronomer Johann Franz Encke analyzed the results of both 18th-century transits, he settled on a value of 8.58 arc seconds for the solar parallax, which corresponded to a mean distance for the sun of 95.25 million miles. Thirty years later, however, Danish astronomer Peter Andreas Hansen argued, based on perturbations of the moon’s motion caused by the sun’s gravity, that the sun must be considerably closer. This claim gained further support in 1862, when measurements of the parallax of Mars—determined by comparing the planet’s position in the sky from two widely separated observation points—gave estimates between 91 million and 92.5 million miles for the astronomical unit. Thus, on the eve of the 19th-century transits of Venus, the distance to the sun was still a value of considerable uncertainty. British Astronomer Royal

THE AUTHOR

STEVEN J. DICK is chief historian for NASA. For 25 years he was an astronomer and historian of science at the U.S. Naval Observatory, the institution that led the American transit of Venus expeditions in 1874 and 1882. He is author of *The Biological Universe*, *Life on Other Worlds* and, most recently, *Sky and Ocean Joined: The U.S. Naval Observatory, 1830–2000* (Cambridge University Press, 2003). The latter includes a detailed historical chapter on the transits of Venus. He is past president of the History of Astronomy Commission of the International Astronomical Union and now serves as chairman of its Transit of Venus Working Group.

George B. Airy said at midcentury that determining the solar parallax was “the noblest problem in astronomy.” Agnes Mary Clerke, a 19th-century astronomy historian, wrote that the solar parallax was “the standard measure for the universe . . . the great fundamental datum of astronomy—the unit of space, any error in the estimation of which is multiplied and repeated in a thousand different ways, both in the planetary and sidereal systems.”

Desperately Seeking Parallax

BY 1857 AIRY HAD FORMULATED a general plan for observing the 1874 transit of Venus, and by 1870 Britain was constructing the necessary instruments. Similar plans were under way in other parts of the scientific world. As the much anticipated event approached, no fewer than 26 expeditions were launched from Russia, 12 from Britain, eight from the U.S., six each from France and Germany, three from Italy and one from Holland. “Every country which had a reputation to keep or to gain for scientific zeal was forward to co-operate in the great cosmopolitan enterprise of the transit,” Clerke wrote. The colorful history of these expeditions would take a book to describe; each has its own story, and each met varying degrees of success or failure.

Simon Newcomb of the U.S. Naval Observatory—the leading astronomical institution in America at that time—urged the National Academy of Sciences to take up the problem. Congress formed an American Transit of Venus Commission, in which Newcomb and other Naval Observatory astronomers played a prominent role. The commission outfitted a total of eight expeditions for the 1874 event—three to the Northern Hemisphere and five to the Southern. In all, Congress appropriated the munificent sum of \$177,000, equivalent to more than \$2 million today.

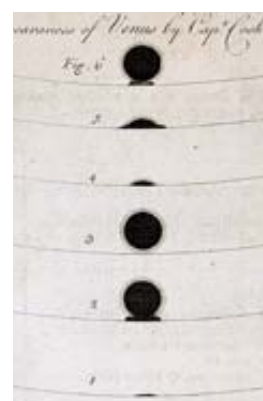
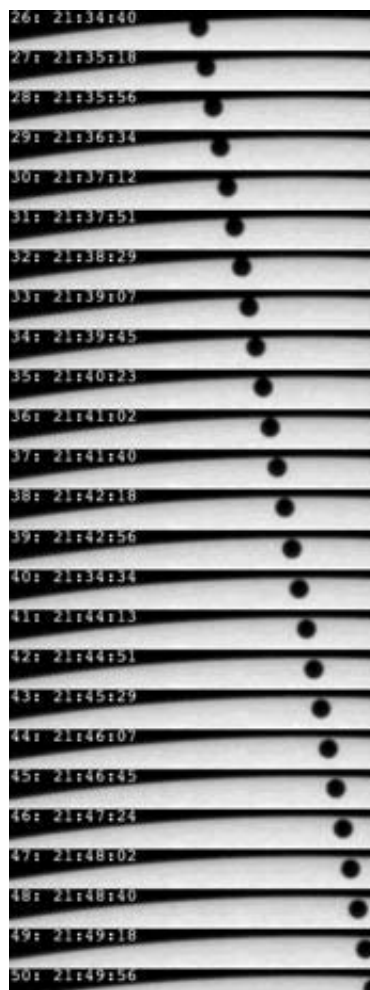
Each expedition was equipped with elaborate instrumentation. To visually observe the moments of contact between Venus and the sun, the researchers employed a refractor telescope with a five-inch-wide lens made by Alvan Clark and Sons, the premier telescope maker in 19th-century America. The scientists were also able to photograph the sun using a photoheliograph, an instrument that had been invented only two decades before. Sunlight was directed through a fixed horizontal telescope, which had a focal length of 40 feet, by a slowly turning mirror that kept the sun’s image stationary. The telescope produced images of the sun four inches in diameter, allowing astronomers to track Venus’s movement precisely across the solar disk.

SCIENTIFIC AMERICAN, which avidly followed the progress of the expeditions, reported in its September 26, 1874, issue that the ship *Swatara* carrying the U.S. observation parties bound for the Southern Hemisphere had made the trip from New York to Brazil in a speedy 35 days. The Europeans, for the most part, opted for a different photographic setup: smaller telescopes with shorter focal lengths. Their equipment was designed to yield high-quality photographs, but because their images would be smaller than those of the American teams, measuring Venus’s position against the sun would be more difficult.

When the transit finally took place on December 9, 1874,

bad weather stymied many of the expeditions. Worse, when the astronomers analyzed the visual contact observations, they soon found that the results were no better than those recorded in the 18th century. Around the world the problem was the same. William Harkness, the U.S. Naval Observatory astronomer who led the observation party at Hobart Town on the Australian island of Tasmania, stated that “the black drop, and the atmospheres of Venus and the Earth, had again produced a series of complicated phenomena, extending over many seconds of time, from among which it was extremely difficult to pick out the true contact.”

The photographic observations were thus all the more important, but here again disappointment was widespread. Harkness recalled that “it soon began to be whispered about that those taken by European astronomers were a failure.” The official British report declared that “after laborious measures and calculations it was thought best to abstain from publishing the results of the photographic measures as comparable with those deduced from telescopic view.” As Harkness noted, it was impossible to determine accurately Venus’s position against the sun because the researchers could not pinpoint the boundary of the solar disk: “However well the sun’s limb on the photograph appeared to the naked eye to be defined, yet on apply-



BLACK-DROP EFFECT was observed by British explorer Captain James Cook during the 1769 transit of Venus. A drawing based on Cook's observations (above) shows the limb of Venus clinging to the sun's perimeter, making it impossible to determine the exact moment of contact. Cook speculated that the cause was an atmosphere around Venus. But in 1999 the Transition Region and Coronal Explorer (TRACE) spacecraft recorded a similar phenomenon during a transit of Mercury, which has no atmosphere (left). The cause of the black drop is still controversial.

ing to it a microscope it became indistinct and untraceable, and when the sharp wire of the micrometer was placed on it, it entirely disappeared.” The French did publish their results, but with wide error bars.

All hope focused on the American expeditions, which had returned with about 220 measurable photographic plates taken with the long-focus photoheliographs. A value for the solar parallax of 8.883 arc seconds was published in 1881, on the eve of the next transit. But the results were sufficiently ambiguous that many astronomers, including Newcomb, argued that the transit of Venus was not a good method for determining the astronomical unit. Harkness, though, never lost faith, and with additional congressional appropriations, the U.S. mounted eight more expeditions to observe the transit of 1882. After analyzing the photographs of this transit for almost a decade, Harkness concluded that the best estimate of the solar parallax was 8.809 arc seconds, yielding a sun-Earth distance of 92,797,000 miles, with a probable error of 59,700 miles. The actual average distance, now measured precisely through spacecraft observations and other techniques, is 92,955,859 miles. (The corresponding value of the solar parallax is 8.794148.)

How important were the transit of Venus observations to the history of astronomy? Although Newcomb, whose system of astronomical constants would be used internationally for most of the 20th century, adopted a value for the solar parallax that was quite close to Harkness’s, he gave the transits of Venus a very low weight compared with other methods for estimating the constant. In his opinion, the black-drop effect and other errors greatly impaired the transit’s use for determining the astronomical unit.

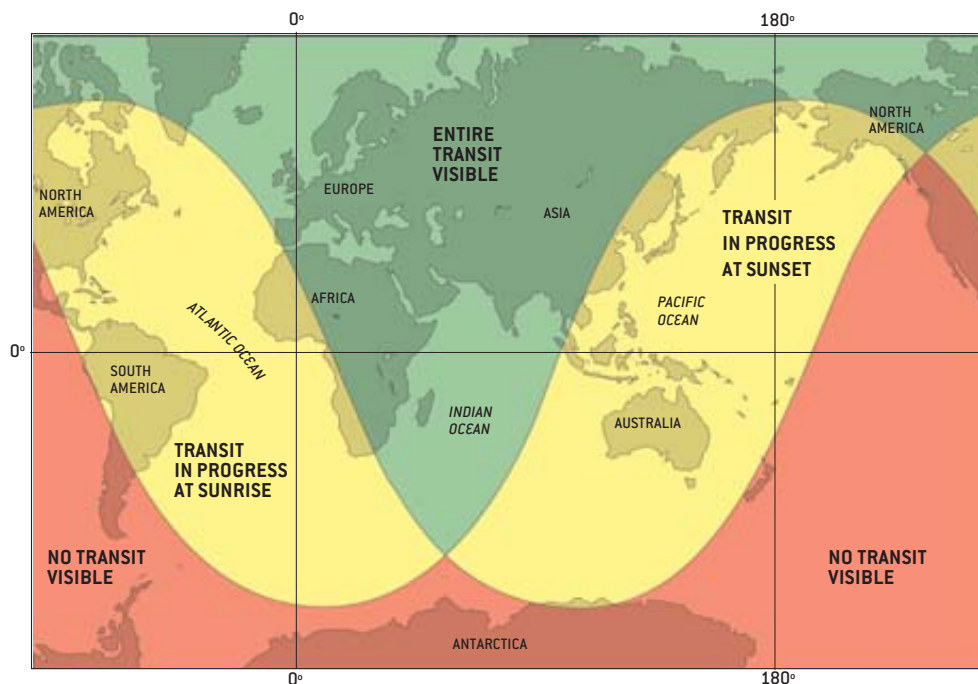
Interestingly, the cause of the black-drop effect is still a subject of much controversy. Eighteenth- and 19th-century as-

tronomers attributed it to a variety of sources, including the atmospheres of both Earth and Venus. But when scientists used the Transition Region and Coronal Explorer (TRACE) spacecraft to observe the 1999 transit of Mercury—a planet with no atmosphere, viewed from a satellite far above Earth’s atmosphere—they still saw a weak black-drop effect [see *left illustration on preceding page*]. Although this finding does not preclude atmospheric effects strengthening the black drop, the underlying cause must be something else.

The TRACE team (led by Glenn Schneider of the University of Arizona’s Steward Observatory, Jay M. Pasachoff of Williams College–Hopkins Observatory and Leon Golub of the Smithsonian Astrophysical Observatory) concluded that the black drop is caused partly by optical smearing between the planetary and solar disks. To see a similar phenomenon, hold your thumb and forefinger very close together and view the narrow gap against a bright background; a dark “ligament” will appear between them even when they are not touching. In addition, solar limb darkening—the lessening of brightness at the sun’s edge—also contributes significantly to the black drop. The TRACE researchers suggested that the effect might be mitigated using new techniques for the upcoming Venus transit.

Safety First!

ALTHOUGH TRANSITS OF VENUS are no longer important for determining the astronomical unit, this year’s event is sure to be one of the most widely observed in astronomical history. It is possible to see Venus against the sun without magnification and certainly with binoculars or a small telescope, but Fred Espenak of the NASA Goddard Space Flight Center warns that viewers must take the same precautions that are employed for a solar eclipse. Looking at the sun through a telescope without



BEST PLACES to observe the June 8, 2004, transit of Venus are in Europe, Africa and Asia (*left*). Sky watchers in Australia and the eastern U.S. will be able to see only parts of the transit; people in the western U.S. will miss the event completely. To avoid eye damage, observers *must* use appropriate solar filters when viewing the transit (*above*). More information about safety precautions can be found on the Web at www.transitofvenus.org/safety.htm

NINA FINKEL (*left*); CHUCK BUETER (*right*)

“When the last transit season occurred the intellectual world was awakening from the slumber of ages....”

—William Harkness, 1882



an appropriate filter can cause instant eye damage and permanent blindness.

One of the safest ways to see the transit is to project the image of Venus and the sun onto a piece of paper. Using time-honored occultation techniques, amateur astronomers can make useful observations of the timings of contacts, which they should send (along with their geographic coordinates) to the Mercury/Venus Transit Section of the American Association of Lunar and Planetary Observers. After the 1882 transit, many sky-gazers sent reports to the U.S. Naval Observatory that are still preserved in the National Archives.

The 2004 Observer's Handbook of the Royal Astronomical Society of Canada has gone to the trouble of detailing the average frequency of cloud cover at the time of the transit for locations around the globe. According to the handbook, the best observation spots are in Iraq, Saudi Arabia and Egypt, with the optimal site being Luxor, Egypt, which has a 94 percent chance of clear weather based on historical records. For this reason, at least one cruise line is heading for the Nile.

Just as the 1882 transit stirred the celestial interests of the young George Ellery Hale and Henry Norris Russell—two astronomical pioneers of the 20th century—perhaps the 21st-century transits of Venus will also encourage young people to study astronomy. Hoping to make the most of the educational opportunities, NASA's Office of Space Science is sponsoring a wide array of events designed to involve students and the general public. A consortium of European institutions has made similar plans. What is more, the “Transit of Venus March,” composed by the legendary American composer John Philip Sousa after the 1882 transit, has been resurrected and is being performed with increasing frequency after going unplayed for more than 100 years.

Extrasolar Transits

MEANWHILE PROFESSIONAL astronomers around the world will be celebrating the transit even as they study it. While scientists are training ground-based telescopes and spacecraft instruments at the sun, the International Astronomical Union will hold a meeting near the place where Horrocks viewed the 1639 transit. The IAU's Working Group on Transits of Venus is encouraging the placement of memorial plaques at the sites of previous transit observations.

The transit of Venus still intrigues researchers because it offers a rare opportunity to develop techniques for detecting and characterizing planets in other solar systems. Most of the 120

extrasolar planets discovered to date have been found because their gravity causes small periodic motions in the stars around which they orbit. In 1999, however, astronomers announced the first detection of a planet by measuring a diminution of the light from a star as the planet passed between it and Earth. Located 153 light-years from our solar system, the planet reduced the light from its star by 1.7 percent during the three-hour transit. Unlike conventional planet-finding techniques, transit observations allow astronomers to determine the orbital plane of the extrasolar planet, from which its mass can be deduced. And because the amount of light diminution indicates the size of the planet, scientists can estimate the body's density.

Now NASA is planning to use a spacecraft to find other extrasolar planets by observing their transits. Scheduled for launch in 2007, the Kepler probe will monitor 100,000 sunlike stars over four years. Because photometers can detect tiny decreases in the brightness of a star, the craft will be able to discover planets as small as Earth. Observations of this year's transit of Venus could help researchers calibrate the instruments for making these breakthroughs.

Thus, the story of the transit of Venus has come full circle from Kepler the man to Kepler the spacecraft. Newcomb, Harkness and their contemporaries would surely be amazed at the progress of astronomy since the last transit in 1882. And what will be the state of science and civilization when Venus again approaches the sun in 2117? It is quite possible that by that time a transit of Earth will have been observed from Mars, as foretold by Arthur C. Clarke. If there are humans on Mars on November 10, 2084, they will see their home planet move slowly across the face of the sun, a black dot against a brilliant background. It will surely be a poignant moment and another milestone in the history of planetary transits and human exploration. SA

MORE TO EXPLORE

June 8, 2004: Venus in Transit. Eli Maor. Princeton University Press, 2000.

The Transit of Venus: The Quest to Find the True Distance of the Sun. David Sellers. Magavelda Press, 2001.

The Transits of Venus. William Sheehan and John Westfall. Prometheus, 2003.

More information on the transits of Venus can be found at www.transitofvenus.org and sunearth.gsfc.nasa.gov/eclipse/transit/transit.html

NASA's educational and public outreach plans are detailed at sunearth.gsfc.nasa.gov/sunearthday/2004/index_vthome.htm

European plans are described at www.eso.org/outreach/eduoff/vt-2004/index.html