The Transit of Venus:

Twice in a Lifetime

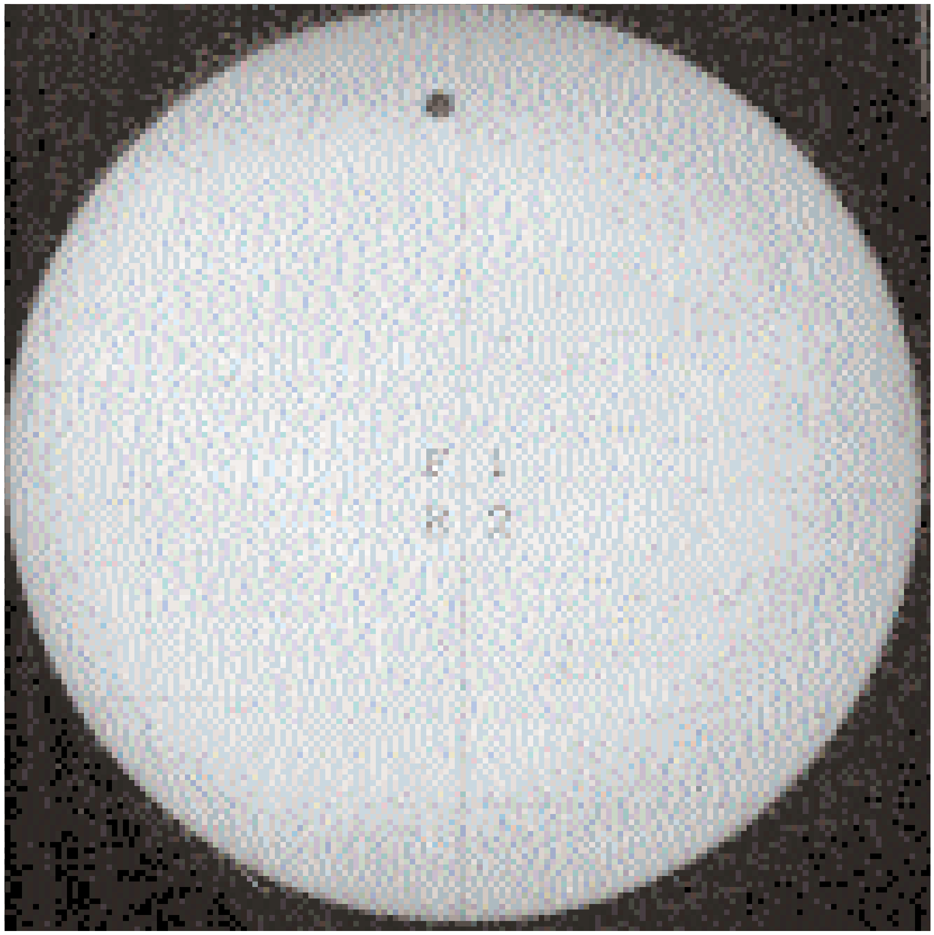
On the 8th of June Venus will pass across the face of the Sun—a rare event that in the 17th century permitted European scientists to determine the size of the Solar System.

by Louis Mayo

Where will you be on 8 June 2004?

If you don't yet know, you had better decide quickly or you may miss one of the rarest events in astronomy: the passage of Venus's dark silhouette across the bright disk of the Sun.

Such a "Venus transit" or "transit of Venus" will happen on June 8th of this year, again on June 6th in 2012, but after that not again until 2117. Besides being a geometric rarity, this type of celestial conjunction was once hugely important for astronomers trying to answer some of the most fundamental and central questions in astronomy: How far away is the Sun? How big is the Solar System? Is the Sun really at the Solar System's center? How far away are the stars? Upon answers to these questions are built many of the pillars of modern astronomy, and it is with this humbling thought in mind that we begin a story of discovery.



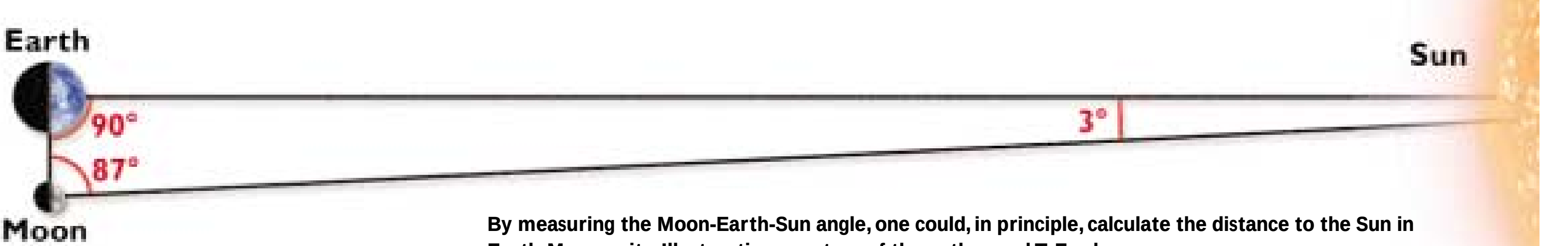
One of the eleven surviving glass plates from eight U. S. eclipse expeditions in 1882. Plate image courtesy of U. S. Naval Observatory Library.

Transit History

For centuries, astronomers, philosophers, and theologians have sought to place mankind and Earth in their proper places in the Universe. Early attempts to do this were based more on philosophy and religion than science with its observations, testable hypotheses, and theories. Yet for much of written history, astronomers lacked the tools needed to interpret their observations of the sky. The magic of geometry and, later, trigonometry, coupled with carefully made observations, provided a powerful tool that could be used to make the first scientific estimates of celestial distances.

The Greeks developed the first known model of the cosmos and based it upon systematic behavior of the stars and planets. Around 500 B.C.E., Pythagoras suggested that Earth is round because a sphere is a perfect shape, and the gods would certainly not have made a celestial object less than perfect. Later, sometime about 400 B.C.E., Plato suggested that the Universe is Earth-centric and that all celestial objects move in perfect spheres around our Earth.

Aristotle concluded that Earth is a sphere because the shadow cast on the Moon during lunar eclipses is always curved and because, as he traveled southward, previously unseen stars emerged from the horizon. He also believed that celestial motion is perfect and that the four Earthly elements (fire, water, air, and earth) are inherently flawed and very different from the material that makes up, and the science that describes, the celestial world.



By measuring the Moon-Earth-Sun angle, one could, in principle, calculate the distance to the Sun in Earth-Moon units. Illustaration courtesy of the author and T. Ford.

Seeing the Transit Safely

Never look directly at the Sun, and don't even think about looking at it through a telescope that has not been properly filtered!!! Okay, now that I've said that…there are a number of fun ways to look at the Sun safely and without risk of injury to your eyes.

The safest and most economical methods involve projection of a solar image onto a clear surface. Schools may find effective the "Sunspotter," a nice device based on the projection principle and manufactured by Learning Technologies. This instrument projects a 3-inch image of the Sun onto a piece of paper and makes it practically impossible for a child to look through the lensing system.

A cheaper alternative is to purchase an inexpensive pair of binoculars, set them on a tripod, and project the image coming out of one of the eyepieces onto a piece of paper. Note: do not leave this set-up unattended as people will naturally want to look through the eyepiece. And for a do-it-yourselfer, make your own solar observing box (a pinhole camera) out of a cardboard box, aluminum foil, and tape.

If you wish to use a telescope, you can purchase a neutral-density solar filter for it (usually for \$50-\$100). A number of places sell these filters—businesses like Orion Telescopes and Thousand Oaks Optics. Also, Coronado Filters sells a pair of 10 x 25 Roof Prism binoculars with integral white light filters, called "Binomite," for around \$50. These filters allow you to see the Sun's photosphere, including sunspots, but will not show solar prominences or much surface detail. To see details, you will need a telescope fitted with a filter that passes only the 6563-Å line of hydrogen. These H-alpha filters can be very expensive, from hundred to thousands of dollars. — *L.M.*

For more information, or if you wish to purchase some goods for the transit or general solar viewing, check out these sites:

Safe Solar Viewing
www.spaceweather.com/sunspots/doityourself.html
victoria.rasc.ca/articles/2000/art0004.html
sunearth.gsfc.nasa.gov/eclipse/SEhelp/safety.html

Sunspotter, Learning Technologies
www.learningtechnologiesinc.com

Binomite, Coronado Filters
www.coronadofilters.com

Solar Filters, Thousand Oaks Optical
www.thousandoaksoptical.com

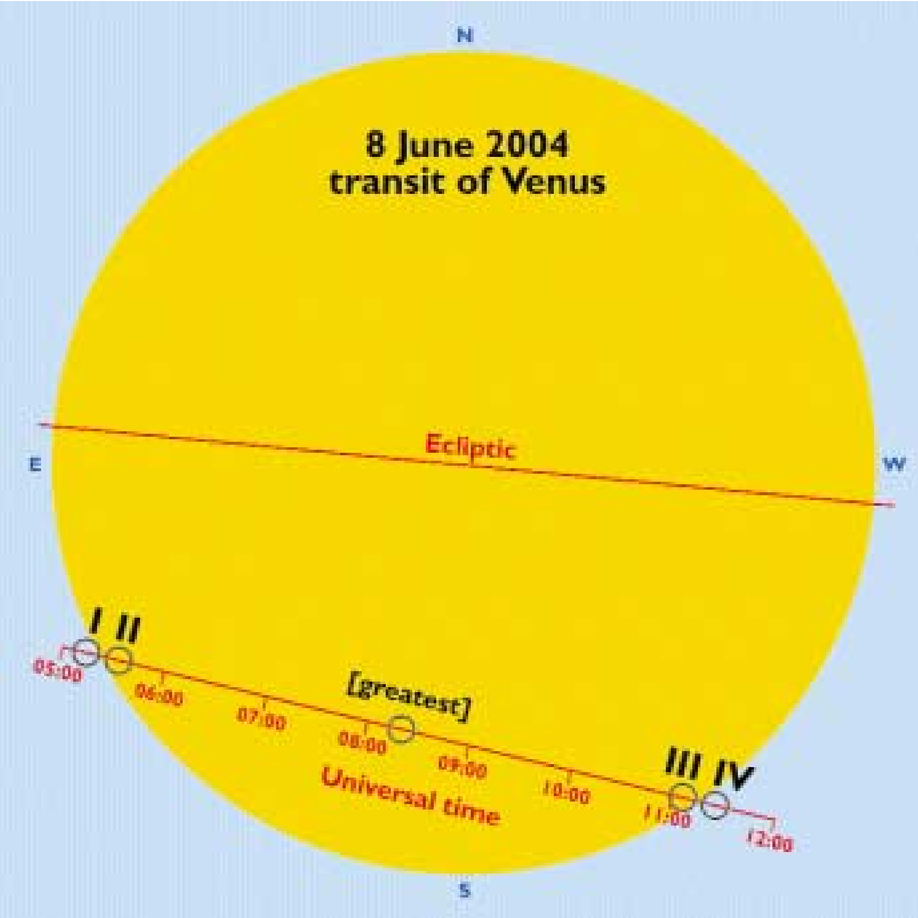
Solar Filters, Orion Telescopes
www.telescope.com

It was Aristarchus of Samos who first proposed a Sun-centered universe. In about 300 B.C.E., he attempted to determine perhaps the first scientifically derived distance to the Sun (now known as the Astronomical Unit, or A.U.) by observing the 1st-quarter Moon. At 1st quarter, the Earth-Moon-Sun angle should be almost 90 degrees. By measuring the Earth-Moon-Sun angle, one could, in principle, calculate the distance to the Sun in Earth-Moon units. Unfortunately, measuring the Earth-Moon-Sun angle is very difficult, and Aristarchus's conclusion that the Sun is about twenty times more distant than the Moon, a result based on his determination that the Earth-Moon-Sun angle is 87 degrees, was a factor of twenty too small. Yet from this low estimate, he concluded that the Sun is approximately seven Earth-diameters wide. Thus, he was the first to suggest that the Sun is very far away and much larger than Earth.

With the Sun so large and observably bright, Aristarchus reasoned that it and not Earth was at the center of the Universe. While his logic was flawed, his conclusion was correct, although it would be almost two millennia before this idea would acquire a solid foothold in scientific circles. One of the most powerful arguments against this Sun-centered model was that if Earth did move around the Sun, why did the stars not seem to change position over the course of the year (i.e., parallax)? It took great minds and increasingly sophisticated technology to answer eventually this question.

In the 2nd century of the Common Era, the Greek astronomer Ptolemy developed a theory of cosmic motion that would be the prevailing view among astronomers for over 1500 years. His great work *Almagest* was based on voluminous and painstaking measurements of the positions and motions of the planets and the stars. In the *Almagest*, Ptolemy put forth a model of the workings of the Universe with Earth at the center, neither rotating nor revolving in an orbit, and with all celestial objects, including the Sun, orbiting Earth on transparent crystalline spheres.

Of course, there were problems with his model. Why, for example, did Mars, as well as some other planets, exhibit periodic retrograde motion? Why did Venus change in brightness over time and, as Galileo finally observed with a telescope 1400 years after publication of the *Almagest*, exhibit phases like the Moon? If it revolved around Earth in a perfect circle, Venus should maintain the same apparent brightness. In order to account for these confusing departures from observation, Ptolemy introduced the concept of epicycles—smaller spheres on which planets orbited as they simultaneously moved around Earth. Over time, his suc-



The geometry of the 2004 Venus transit. Times of "contacts" (I, II, III, IV; see text) are given in Universal Time. Illustaration courtesy of the author and T. Ford.

Greek Claudius Ptolemy (ca. 85 - ca. 165) recorded his thoughts on and observations of the heavens in the *Almagest*.

Measuring Parallax

Parallax is a visual effect observed when close-by objects are seen in relation to faraway objects. It occurs because of differences in the viewing angle of the observer. To demonstrate this, hold your finger at arm's length. With one eye closed, observe where your finger appears to sit against some more distant background. Now, keeping your finger at arm's length, close the one eye and open the other: your finger should appear to move against the background. Blinking back and forth will demonstrate the magnitude of the displacement. Now do the same thing but with your finger held much closer to your face. You should observe a larger displacement. This effect is called *parallax* and can be used to determine the distances to celestial, as well as Earthly, objects.

In the case of the transit of Venus, the planet takes the place of your finger, the solar disk is the backdrop, and observations from two different places on Earth represent each of your eyes. The key to deriving the distance to Venus lies in knowing the angular measure of the Sun (about 30 arc minutes or 1/2 degree) and the distance between the two observers. The small-angle formula then provides an easy way to compute the distance to Venus. Once an absolute distance is known, Kepler's third law, $P^2 = a^3$, with a measured in AUs and P in years, can be used to figure the distances to all the planets and to the Sun. — *L.M.*

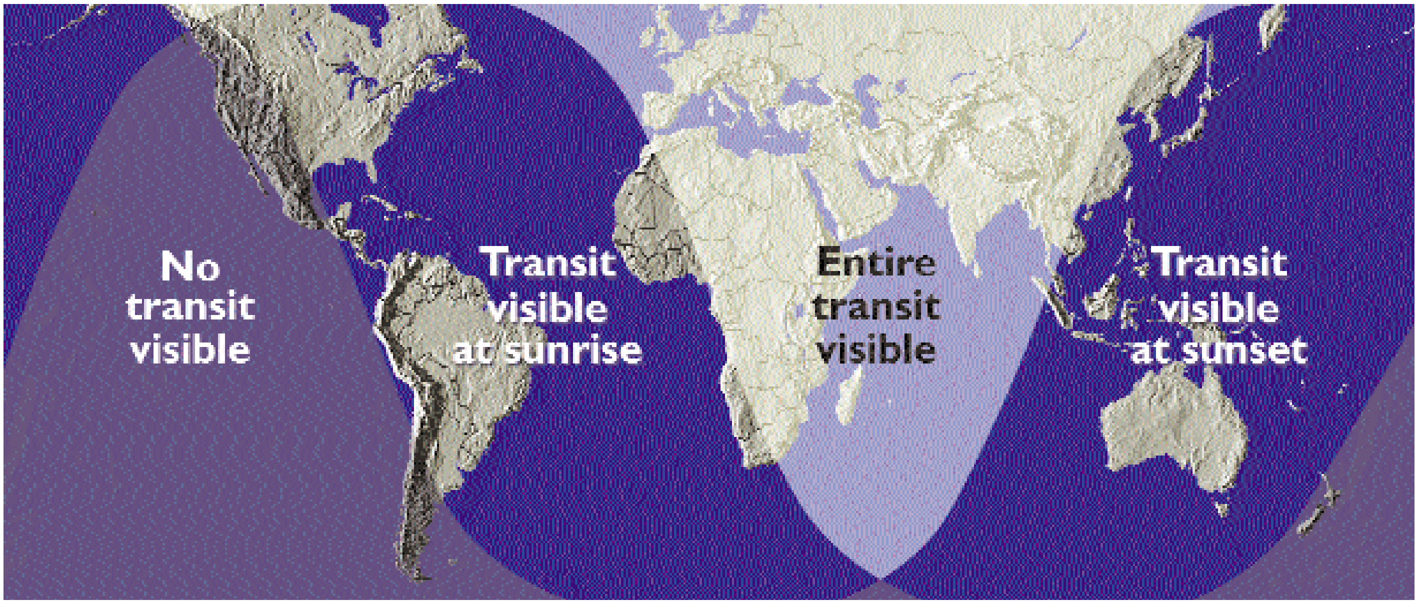
cessors would add more and more epicycles in attempts to account for still unexplained departures from observational evidence.

It would take such minds as Galileo, with his detailed telescopic observations of Venus and the Jovian moons in the early 17th century, and Kepler, through his analysis of many planetary positional measurements of Ptolemy and Kepler's mentor, Tycho Brahe, to finally get it right. The planets all orbit the Sun in elliptical orbits. Though many students of astronomy in 17th century Europe still subscribed to the Ptolemaic system, the stage was set to begin the drama of determining the true size of the Solar System and eventually, the distances to the stars.

The transit of Venus was a critical element in this drama, and the determination of the size of the Astronomical Unit was lead actor. Using the method of parallax (see "Measuring Parallax," at left), Jeremiah Horrocks, an observer to the 1639 transit, and Edmond Halley, who developed the first detailed plan for calculating the A.U. using a transit of Venus, lead the charge in deriving a much improved Sun-Earth distance.

The Geometry of the Situation

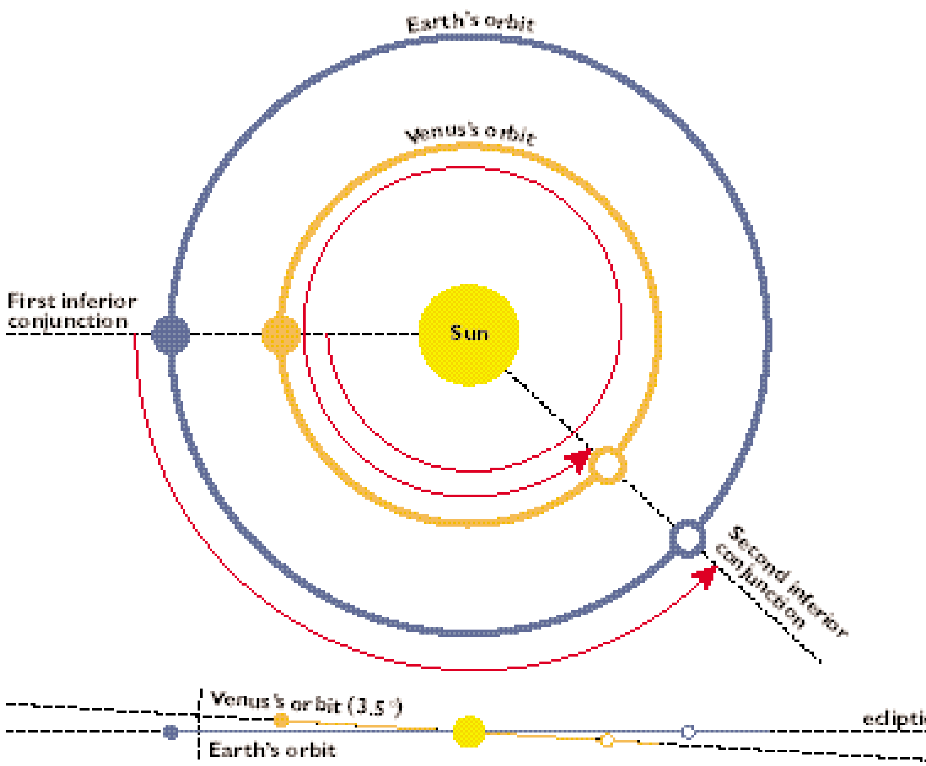
All nine planets—yes, I still count Pluto a planet!—orbit the Sun in the same direction though not all in quite the same orbital plane. The reference plane, or ecliptic, is defined by Earth's orbit around the Sun.



Visibility map for the 8 June 2004 transit of Venus. Map courtesy of F. Espenak and T. Ford.

Venus's orbit is tilted by 3.5 degrees to the ecliptic. Remembering that the Sun subtends an angle of only about 1/2 degree in the sky, it is easy to see why there is not a transit of Venus every time it is at inferior conjunction: Venus is usually either too low or too high to be seen against the Sun.

Let's consider the geometry of the situation a little more. The ecliptic and Venus's orbital plane intersect along a line, and the two points at the end of this line are called the ascending and descending nodes. It is only when Venus is at inferior conjunction with Earth (between our planet and the Sun) and Earth is near one of these two points that a Venus transit can occur. Since the orbital periods of Venus (224.701 days) and Earth (365.256 days) are in an eight-year resonance with each other (Venus makes thirteen revolutions around the Sun in the same time that Earth completes eight), one might conclude from this that a transit of Venus would occur at least every eight years. But because Venus reaches its ascending or descending node in slightly less than eight Earth years (2921.11 days vs. 2922.05 days), Venus and Earth must wait between 105.5 and 121.5 years to be back in the proper alignment. "Paper Plate Astronomy," a website by Chuck Bueter and at *analyzer.depaul.edu/paperplate/transit.htm*, provides an easy and fun activity demonstrating these concepts.



Geometry of a Venus transit. Venus orbits the Sun almost exactly thirteen times for every eight orbits Earth completes around the star. This close resonance is responsible for the timings of Venus transits. Illustaration courtesy of the author and T. Ford.

The Day: 8 JUNE 2004

On the 8th of June, observers in eastern parts of Canada, the United States, and South America, as well as all parts of Europe and Africa and most of Asia, will be treated to the rare Venus transit (visit *www.melita-trips.com* for information on how you can join an ASP transit trip). The general progression of the transit is as follows: at 05:13:29 UT, Venus will appear as a small, dark disk just making contact with the Sun's southeastern edge (1st contact). Its disk will subtend about one arcminute, or about 1/30th the diameter of the Sun, so Venus will be easily visible using simple solar-projection devices. The planet will continue along a chord stretching from the southeast to the southwest and will pass beyond the Sun (4th contact) at 11:25:59 UT.

In eastern regions of the Americas, the Sun will rise with Venus already in transit. Observers in these regions will see third and fourth contact—the point at which Venus is just beginning to leave the Sun's face and the point at which the planet has completely left the Sun, respectively—and be able to observe the transit for between about one hour (in Florida), two and a half hours in Maine, and correspondingly less time the further west the observer. Fred Espenak's website *sunearth.gsfc.nasa.gov/eclipse/transit/TV2004.html* provides detailed transit times for most places on Earth.

Research—What's Left?

Most of the value in Venus transits is now historical, but in the past the events provided the yard stick with which the Universe could finally be measured. However, I am aware of at least two research teams who will be using the transit on 8 June to probe Venus's thick atmosphere. One group, led by Anthony Mallama (Raytheon ITSS), will use the small phase angle produced as Venus nears the solar limb, or edge, to explore the particulate properties of the Venusian atmosphere. Venus should appear brighter at small phase angles due to Mie scattering of particles smaller than 100 microns. Mallama and his research colleagues hope to model this function, identify the material responsible for it, and determine particle size and abundance. The best guess is sulfuric acid droplets.

Jay Pasachoff (Williams College) and Leon Golub (Harvard-Smithsonian Center for Astrophysics) will use the TRACE satellite to study the "black-drop" effect in x rays to confirm their mathematical model, which explains the origin of the effect in terms of instrument characteristics. The "black-drop" effect has been observed and photographed during transits of Venus and smaller Mercury: at 2nd and 3rd contact, a small, dark band appears to form between the transiting planet's silhouette and the Sun's limb. The band appears to connect the planet's silhoutte and the solar limb. This apparition, long attributed to Venus's atmosphere, is visible even for Mercury, which has an insignificant atmosphere. More than a curiosity, the "black drop" effect in the past led to incorrect timings of the transit contacts, and this temporal blurring introduced inaccuracies in estimates of the size of the Astronomical Unit.

Teachers learning safe ways for them and their students to observe the Sun and the transit of Venus. Photo courtesy of the author.

How You Can Participate

Though real research potential is small, the wonder and excitement of this event has not been lost on NASA. The agency views the Venus transit as a marvelous opportunity to communicate with the public and to provide educational resources for teachers and students in astronomy and space science through interdisciplinary topics involving such diverse fields as mathematics, technology, world history, geography, and even music. To accomplish this, NASA has entered into partnerships with museums and planetaria, amateur and professional astronomers, and schools across the United States and Europe. One such partnership involves creation of an observing certificate program for the Astronomical League (*astroleague.org*)—astronomers in the program gain recognition for making transit observations and holding public seminars.

The NASA Sun-Earth Connection Education Forum (website at *sunearth.gsfc.nasa.gov*) is leading the development and deployment of these programs, and anyone can get in on the fun as a teacher, student, scientist, museum director, or just an interested citizen by registering at *sunearthday.gsfc.nasa.gov*. There you will find a mountain of information on the transit including multimedia resources, activities, interviews with scientists, local events, educator guides, and tips and techniques for safe transit-viewing (see "Seeing the Transit Safely," p. 15). In addition, you will be able to view near realtime images of the transit taken by solar observatories that stretch from Nova Scotia to Florida to South America. Each observatory will produce slightly different views of Venus's disk on the Sun due to the parallax effect (note for teachers: by studying these images, your students will be able to calculate the distance to Venus and even determine the length of the Astronomical Unit). Further, the site also provides historical and cultural connections: you can listen to an interview with a Lakota Indian tribal leader or download and then listen to a performance of the 1882 "Venus Transit March" by John Philip Sousa. Finally, you will find at the site instructions for safely viewing the transit and information on the webcast to be broadcast from Athens, Greece on June 8th. After registering at the site, you may also request to receive a packet of materials to use in your classroom, museum, or astronomy club. m

LOU MAYO is a planetary scientist and program manager working for Raytheon at the NASA Goddard Space Flight Center. His chief research interest is the atmosphere of Titan. In addition to being author of the regular Mercury column, "Celestial Wonderings," he is also heavily involved in communicating science to the public through astronomy clubs, educator workshops, robotic telescopes, and public talks.