Venus: it's now or never

Transits of Venus, in which our sister planet passes across the face of the Sun, are predictable but exceptionally rare events. With the next transit due to take place on 5 and 6 June this year, **Jay M Pasachoff** explores the science and history of these twice-in-a-lifetime occurrences

Jay M Pasachoff is an astronomer at Williams College, Williamstown, Massachusetts, US, e-mail eclipse@williams.edu

One of the most exciting recent developments in astronomy has been our ability to detect planets orbiting stars other than our Sun. Astronomers have so far spotted more than 700 such exoplanets, which has made the eight planets in our solar system – 13 if you include the dwarf planets Pluto, Ceres, Eris, Haumea and Makemake – perhaps less special than we once thought. Most of these exoplanets are detected as they cross the face of – or "transit" – their parent stars. But spotting these planets from the faint dimming of their star's light is a fiendish task because several things can, at least for a while, mimic this tiny dip. Indeed, of the thousands of additional possible planets we have seen, thanks in part to the French CoRoT and US Kepler spacecraft, some may just be sunspots.

What can aid our search for exoplanets, however, is studying examples of transits in our own solar system. Doing so not only yields an improved understanding of our own cosmic neighbourhood, but also verifies that the techniques for studying events on and around other stars hold true in our own backyard. In other words, by looking up close at transits in our solar system, we may be able to see subtle effects that can help exoplanet hunters when viewing distant suns. The snag is that, here on Earth, just two planets lie between us and the Sun – Mercury and Venus. And, moreover, they cross the Sun only very rarely.

While transits of Mercury occur about 14 times a century, transits of Venus are even scarcer. They always take place in pairs eight years apart, with the gap between the second transit of one pair and the first transit of the next alternating between 105.5 and 121.5 years. In other words, the transits of 1631 and 1639 – around the time that Galileo was imprisoned by the Church – were followed, after a gap of 121.5 years, by a pair in 1761 and 1769, not long before the American Revolution. The next transits occurred 105.5 years later, in 1874 and 1882, and so, continuing this sequence, the transit of 2004 will be followed by another this year – on Tuesday 5 June in the Americas and Wednesday 6 June in Europe, Asia and Australia (figure 1). It will be an event well worth watching, as the next transit of Venus will not occur until December 2117, when most of us will be long gone.

Origins of a phenomenon

The notion that Venus could potentially pass across the face of the Sun, when viewed from Earth, can be traced back to the work of Nicolaus Copernicus, whose 1543 book *De Revolutionibus* held that only Mercury and Venus joined our Earth in orbiting around the Sun and thus could pass between those two bodies. In 1627 Johannes Kepler, best known for his three laws of orbits, published his *Rudolphine Tables*, which showed the superiority of the Copernican theory and allowed the positions of the planets in the sky to be calculated more accurately. This work led Kepler to predict that both Mercury and Venus would transit the Sun in 1631.

That year's transit of Mercury was observed by the French scientist Pierre Gassendi, but that of Venus was not visible from Europe and so went unseen. (Although the Venusian transit could, in principle, have been observed in other parts of the world, it was only in Europe that astronomers had access to new-fangled "telescopes".) A few years later, however, the English astronomer Jeremiah Horrocks, working in the village of Much Hoole in Lancashire, extended Kepler's calculations and discovered that the next transit of Venus would occur in late November 1639. Horrocks informed one friend in London and another in Manchester, William Crabtree, of the prospective event.

On the afternoon of the big day, when Horrocks finally returned to Carr House in Much Hoole – having been delayed by a task that was no doubt to do with the local church on that Sunday – he found Venus already silhouetted on the surface of the Sun. Although it was much smaller than he had expected, by using a telescope to project the solar image, Horrocks was able to make careful drawings of what he saw. Crabtree, in Manchester, also saw the transit but was so excited to see Venus's silhouette once the clouds had parted that he neglected to make any scientific observations. With clouds obscuring the view of Horrocks' friend in London, it was Horrocks and Crabtree who therefore become the first two people in the world to see a transit of Venus.

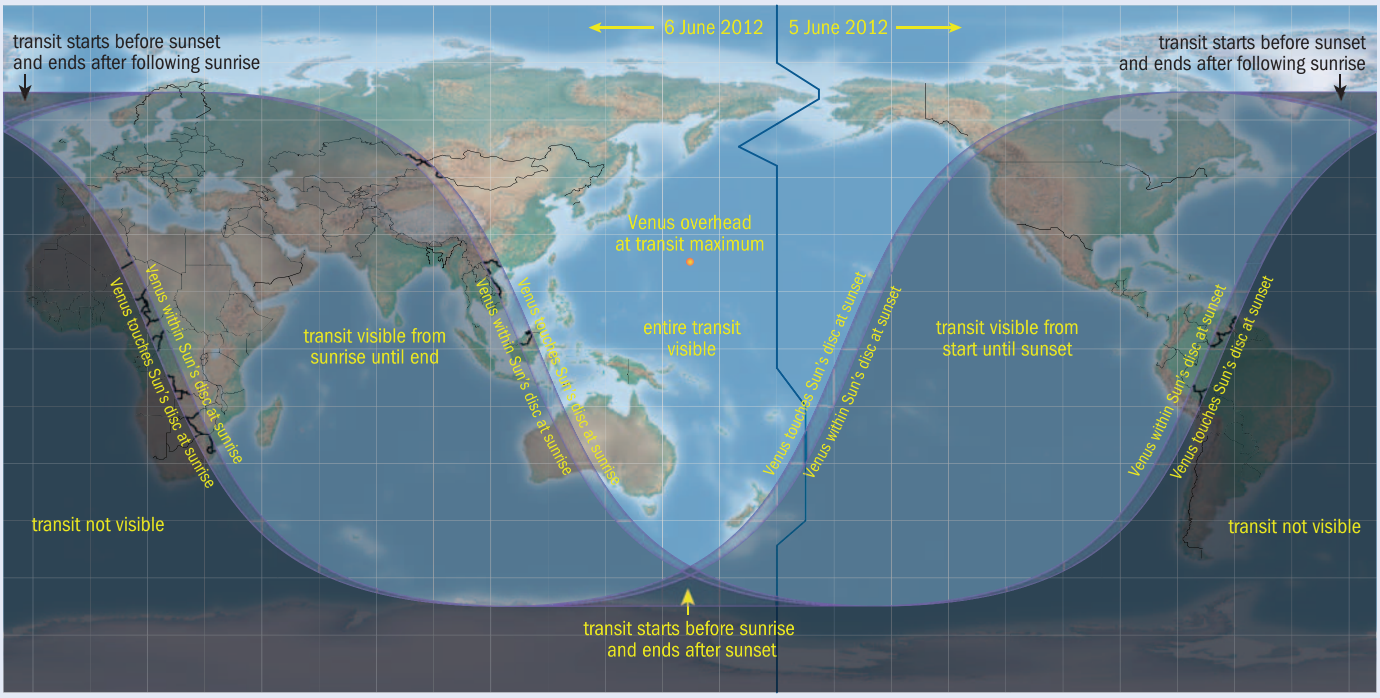
We now know that these transit pairs occur only when Venus's orbital plane crosses the plane of the Earth's orbit around the Sun, the two orbits being at a slight angle of 3.4° to one another (figure 2*a*). One can think of Venus's path crossing the lower half of the Sun, then eight years later passing across the upper half of the Sun, before next time passing above the Sun (and so not being a transit). This process goes on for a further 100 years or so until the angle brings Venus around to the lower half of the Sun again.

Astronomical solution

But transits of Venus are much more than a curiosity. In 1716 Edmond Halley proposed using them to solve what George Airy – then Astronomer Royal – later called "the noblest problem in astronomy":

Jay M Pasachoff, David Butts, Joseph Gangestad and Owen Westbrook (Williams College) with John Seiradakis and George Asimellis (Aristotle University of Thessaloniki); expedition run with Bryce Babcock (Williams College) and Glenn Schneider (University of Arizona)

1 Where to watch the 2012 transit



This year's transit of Venus occurs on Tuesday 5 and Wednesday 6 June, depending on where you are in the world, with the places for seeing it in its entirety being east Asia, Alaska, east Australia, the Pacific islands and New Zealand. Be sure to wear appropriate solar filters when viewing the transit – full safety information can be found at www.transitofvenus.org/june2012/eye-safety and www.transit-of-venus.org.uk/safety.htm.

finding the distance between the Earth and the Sun, known as the astronomical unit (AU). At that time, distances in the solar system were known only proportionately – measured as fractions or multiples of an AU. Measuring the AU would mean that, for the first time, the absolute size and scale of the solar system could be determined.

Halley's method relied on Kepler's third law of orbits, which tells us that the square of the time it takes a planet to orbit the Sun (its period), P^2, is proportional to the cube of the radius of the orbit, a^3. Since we know how long it takes Venus and the Earth to orbit the Sun, then if it were possible to determine the distance to Venus, we could use Kepler's third law to deduce all distances in the solar system, including the AU.

In practice, Halley's method involved observing Venus from two different locations during a transit – one very far north on Earth and one very far south – and accurately determining when the planet first begins to cross the Sun ("ingress") and when it just leaves ("egress"). A transit lasts about six hours and, if it were possible to time the duration to an accuracy of about 1 s, the distance to Venus could then be determined using the principles of triangulation (figure 2*b*). Later in the 18th century an alternative calculation involving accurate timing of only ingress or egress was developed by Joseph-Nicolas Delisle, although the method had its own problems, not least that it required knowing the longitude more precisely than was likely possible at that time.

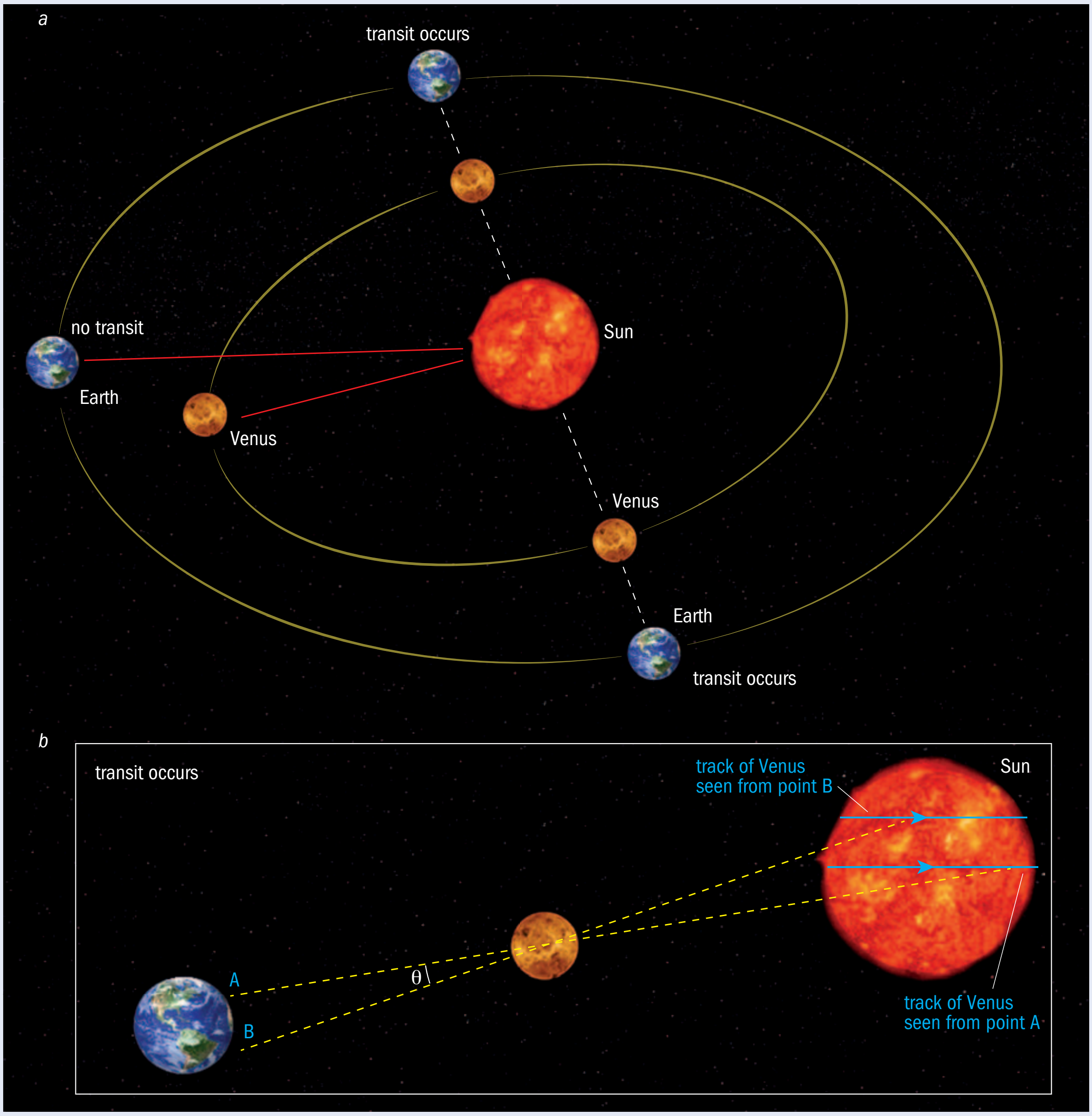
With these methods in hand, hundreds of expeditions were sent all over the world to observe the 1761 and 1769 transits, including the ill-fated voyage undertaken by the French astronomer Guillaume le Gentil (see box on p40). Perhaps the most famous was in 1769, when the British Admiralty entrusted a ship to a young lieutenant by the name of James Cook. Accompanied by former Greenwich astronomer Charles Green and others, Captain Cook took the *Endeavour* to the island of Tahiti in the South Pacific, where they successfully observed the transit under very clear skies at a site that is still called Point Venus. Having completed that task, which was the official reason for the voyage, Cook then opened a letter with secret orders that took him to explore farther south, searching for and mapping a "southern continent", which turned out to be New Zealand and the east coast of Australia.

The black-drop mystery

Unfortunately, when Cook and Green looked through their telescope to time the precise moment of ingress – when Venus was just inside the outer edge (or "limb") of the Sun – they ran into trouble. They noticed a dark band – linking the blackness of Venus's silhouette with the blackness of the background sky outside the solar limb – that grew for about 1 min and then seemed, like pulled taffy, to pop. Now known as the "black-drop effect", it meant that the accuracy of their timing was closer to 1 min than to 1 s, diminishing the accuracy of the calculated astronomical unit by about a factor of 60. Cook and Green mistakenly thought that Venus's atmosphere was causing the uncertainty in the timing, but we now know that the atmosphere is much too small in diameter to cause much blurring.

The two transits of Venus in the 19th century – in

2 Rare but invaluable



(*a*) Transits of Venus occur only on those very rare occasions when Venus and the Earth are in a line with the Sun, That situation only occurs when Venus and the Earth are at locations where their orbital planes intersect. At other times Venus will pass above or below the Sun.
(*b*) Edmond Halley devised a way of determining the distance between the Earth and Venus by observing a transit from two points at very different latitudes on Earth. It involves measuring, from both locations, the time that the planet first crosses the face of the Sun and when it finally leaves about six hours later, which allows the angular shift, θ, to be calculated. Knowing θ and the distance between the two observing locations on Earth (AB), the distance to Venus (about 42 million kilometres) can be calculated using trigonometry. Applying Kepler's laws then gives a value for the distance between the Earth and the Sun, and all other distances in the solar system can be similarly deduced. Both figures are not to scale.

Measuring the distance between the Earth and the Sun meant that, for the first time, the size and scale of the solar system could be determined

1874 and 1882 – were well observed all around the world. Photography was also used for the first time, although the black drop still foiled accurate attempts to measure the AU using Halley's method, as it had done for the 18th-century transits. There having been no transits throughout the 20th century, Glenn Schneider of the University of Arizona's Steward Observatory and I decided in 2001 – three years before the first transit of the 21st century – to try to solve the origins of the black-drop effect once and for all.

We sought to do this by analysing observations of the effect made by NASA's Transition Region and Coronal Explorer (TRACE) spacecraft during the 1999 transit of Mercury. The black-drop effect, it turns out, has two different causes. One, which had been widely suspected, is down to the fact that no telescope is perfect and that even a point source will have a certain inherent fuzziness, known as the "point-spread function". But the other cause, which had previously not been widely acknowledged, is the fact that the visible Sun is always darker near its edge, with the intensity falling off following roughly the path of a cosine curve. Indeed, the drop in brightness, known as "solar limb darkening", is so

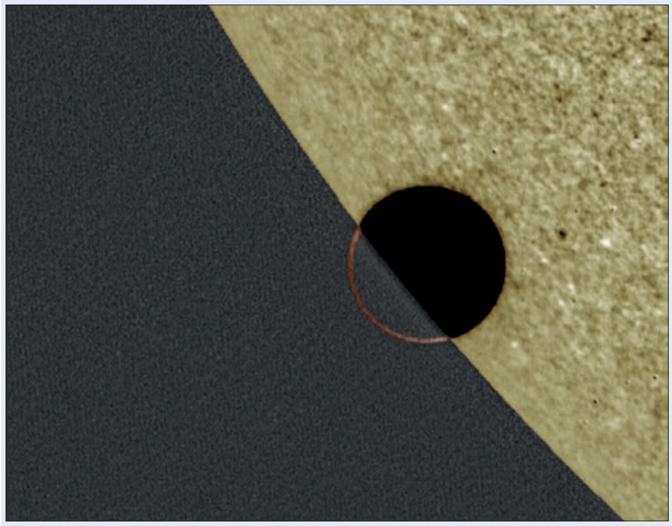
The strange tale of Guillaume le Gentil

There have been some intrepid journeys over the years to view transits of Venus, none more so than that of the 18th-century French astronomer Guillaume le Gentil. In 1761 he set out to observe that year's transit from Pondicherry in south-east India, but the British held the area when he arrived and refused to let him land. Although he saw the transit in clear sky from his ship where he remained, his pendulum clock was useless on board. Le Gentil therefore decided that because the next transit was only eight years away, he would stay in Asia and wait for it to arrive.

Eventually, following spells in the Philippines and elsewhere, Le Gentil returned to Pondicherry for the 1769 transit. But after a promising day of good weather, disaster struck when, having waited eight years for the big day, Le Gentil's view of Venus was spoiled by a cloud. To add insult to injury, on his return journey to Europe, he was shipwrecked and hospitalized for dysentery, before finding, on arriving in France 11 years after his departure, that his fiancée had married someone else and that he himself had been declared officially dead.

So incredible were Le Gentil's efforts that the Canadian playwright Maureen Hunter dramatized them in a production called *The Transit of Venus* in 1998, which was later turned into an opera of the same name by the Canadian composer Victor Davies, with Hunter writing the libretto. Fortunately, Le Gentil's tale had a happy ending, as he eventually regained his place in the French Academy of Sciences, got married and had children. He died in 1792 at the age of 73.

3 What an atmosphere


NASA/LMSAL/Pasachoff, Schneider and Golub

This image of Venus just entering the face of the Sun was obtained with NASA's Transition Region and Coronal Explorer spacecraft during the 2004 transit in collaboration with the author, Glenn Schneider and Leon Golub. It shows the planet as it is part-way across the very edge of the Sun, revealing a bright rim around Venus's trailing edge. This rim is Venus's atmosphere as it bends sunlight towards the spacecraft.

severe in the final arcsecond or so at the edge of the Sun that the limb darkening merges with the point-spread function. Given that Mercury has no appreciable atmosphere and yet shows a black drop, our analysis showed that the black-drop effect need not have anything to do with the existence of a planetary atmosphere. Coupled with our current knowledge of the actual thickness of Venus's atmosphere, we showed that Venus's black drop cannot be caused by its atmosphere either.

With the next transit of Venus due to take place in June 2004, an International Astronomical Union symposium was scheduled to take place at Much Hoole, where Horrocks had observed the first transit all those years ago. Not wanting to take a chance on the notoriously capricious British weather, I took my colleagues and all our astronomy students from Williams College (with the help of a grant from the National Geographic Society, or NGS) to Greece, which lay deeper into the zone from which the whole transit would be visible. In the event, it was clear in Much Hoole after all, but from Greece we were able to observe the whole transit with telescopes and cameras, and I saw the black drop with my own eyes, which was an incredible experience.

Earlier that year, while observing with Sweden's 1 m Solar Telescope on La Palma, which itself went on to make successful observations of that year's transit, I e-mailed the schedulers for TRACE to help them tailor their observations of the transit to meet our requirements. What we particularly wanted to do was to increase the rate at which photographs were taken of the black-drop effect at ingress and egress. But knowing that TRACE can only ever see about a sixth of the Sun at any one time, it was also vital that the craft was pointing in the right direction to see the edge of the Sun. Fortunately, when we got the results, we were relieved that everything had gone well. Moreover, while the planet was roughly halfway into the Sun at ingress, we were flabbergasted to see a bright rim appearing around Venus's trailing edge that persisted and brightened asymmetrically (figure 3). It was, in fact, Venus's atmosphere, which bent sunlight towards us. About six hours later, after Venus had traversed the Sun's disc, we saw the same effect in reverse (2004 *Proceedings IAU Colloquium* **196** 6 and 2011 *Astronomical Journal* **141** 112).

What was also interesting about the 2004 transit was that it extended the study that Schneider and I carried out using measurements obtained by TRACE. William Sheehan and I had been intrigued by claims made by the famous 18th-century Russian scientist Mikhail Lomonosov that he had discovered the atmosphere of Venus after sighting a brief brightness at the edge of Venus during the 1761 transit. However, what Lomonosov reported did not match the 2004 observations studied by Schneider and me, and seemed more like the first appearance of the solar disc at the end of the black-drop effect. Sheehan and I therefore concluded that the Russian must have seen only artefacts and had not discovered Venus's atmosphere itself. But because Lomonosov believed – as did many scientists of his era – that all planets had atmospheres, it is perhaps understandable that he thought he had discovered one around Venus. In the end, he had the right result, but without a proper train of measurement and reasoning.

The 2012 transit

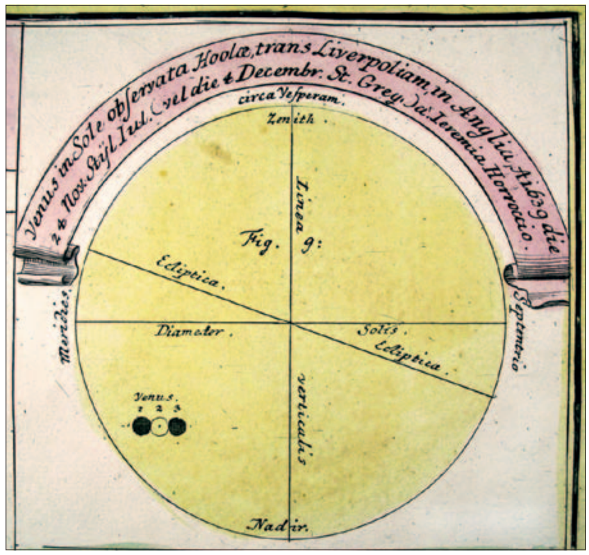
For the upcoming transit of Venus this June we want to get the most complete set of data possible, so that the astronomers of 2117 will think that their forebears way back in 2012 did a fine job even with their relatively primitive instruments. On the ground, I will be at the University of Hawaii's solar observatory on top of Haleakalā – a 3000 m-high dormant volcano – with a couple of my students, as well as Schneider and Bryce Babcock, all supported by a new NGS research grant. We will have several cameras, with the main aim of studying Venus's atmosphere at ingress and egress, while also verifying our previous conclusion about the black-drop effect. Meanwhile, my former student Kevin Reardon of the Arcetri Observatory in Florence, Italy, will be at Sacramento Peak in New Mexico, using a giant imaging spectrometer on the vacuum tower of the Dunn Solar Telescope.

A major part of our research effort will be with telescopes in space, notably using NASA's Solar Dynamics Observatory (SDO), which was launched two years ago as an improved replacement for TRACE. The SDO contains the Atmospheric Imaging Assembly, built by my colleague Leon Golub of the Smithsonian Astrophysical Observatory, which has pixels the same size as those of TRACE but can view the entire Sun at once. The other huge advantage of SDO is that it moves in a geosynchronous orbit and is always in view of a ground station in New Mexico, allowing it to send down eight individual filtered images six times a minute, 24 hours a day (with only a few minor 20 min outages each year when the Earth eclipses the Sun). We will also be co-ordinating our observations with those of colleagues at Stanford University, who run a second SDO instrument, the Helioseismic and Magnetic Imager, which has pixels of a similar size.

This summer Schneider and I will be working again with Richard Willson, who operates NASA's Active Cavity Radiometer Irradiance Monitor satellite from California, in order to monitor the total brightness of the Sun as a way of studying the transit. It follows our successful collaboration in 2004, when we used the same craft to measure the tiny 0.1% drop in the total solar irradiance caused by Venus's silhouette blocking that same fraction of the solar disc. Interestingly, two years later we were unable to detect the 0.003% drop in intensity from the 2006 transit of Mercury because the effect is smaller than the inherent uncertainty in the signal – information that should help exoplanet hunters to know what they might or might not be able to detect. This year's collaboration will also involve Greg Kopp of the University of Colorado at Boulder, whose Total Irradiance Measurement instrument aboard NASA's Solar Radiation and Climate Experiment spacecraft yields similar information.

Beyond 2012

Until recently we had thought that after June there would be no chance to observe any further transits of Venus until the 22nd century. But last autumn we discovered that David Ehrenreich of the Institut de Planétologie et d'Astrophysique de Grenoble, France, had won time on the Hubble Space Telescope to try to observe this June's transit of Venus as it would be if viewed from the Moon. What he plans to do is to point Hubble at several areas on the Moon and monitor the extremely tiny fall in intensity of sunlight reflected off the Moon as Venus passes in front of the Sun. This is obviously harder than studying a transit directly because the intensities involved



Courtesy of the Chapin Library, Williams College

Transits in history Johann Gabriel Doppelmayr published this diagram of the transit of Venus in *Atlas Coelestis* in 1742.

are so low. But the study is useful because it mimics the problems exoplanet hunters encounter, while still occurring in our solar system, where we know exactly what is happening.

But if Hubble could be used to detect the transit of Venus using the Moon, might it also be possible to observe transits of Venus by observing light reflected off the outer planets? After a meeting of the American Astronomical Society in Nantes, France, last October, my transit team met up with that of Ehrenreich to discuss that idea, along with Thomas Widemann of the Observatoire de Paris, Paolo Tanga of the Observatoire de la Côte d'Azur in Nice and Alfred Vidal-Madjar of l'Institut d'Astrophysique in Paris. Since then we have together submitted a proposal for time on Hubble to observe the transit of Venus using Jupiter on 20 September 2012. (If we miss this date, there will not be another transit of Venus from Jupiter until 2024 – long after Hubble's demise.)

Another, even more exciting event will occur on 5 January 2014 when the Earth, as seen from Jupiter, will pass in front of the Sun. Although we cannot view the Earth directly from Jupiter itself, what we can do is to use Hubble to view the Earth indirectly by watching Jupiter's clouds and studying how much of its light bounces off Jupiter's main moon Ganymede. Detecting this transit and any spectral effect from the Earth's atmosphere would be an astonishing feat – and a spectacular verification of our understanding of exoplanet transits.

If we can study transits via Jupiter, what about doing so with Saturn? As it happens, NASA's Cassini craft is currently orbiting the planet and a transit of Venus, as seen from Saturn, is due to take place later this year on 21 December. Together with Phil Nicholson from Cornell University, we have obtained permission from the Cassini board to turn the craft towards the transit on that day, which will be our last chance to see a transit of Venus from Saturn until January 2028. We are fortunate in that we are truly living in a golden period of planetary transits and it is one of which I hope astronomers can take full advantage. ■

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