Transits of Venus: New Views of the Solar System and Galaxy
Proceedings IAU Colloquium No. 196, 2004
D.W. Kurtz & G.E. Bromage, eds.

DOI: 00.0000/X000000000000000X

The black-drop effect explained

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Abstract. The black-drop effect bedeviled attempts to determine the Astronomical Unit from the time of the transit of Venus of 1761, until dynamical determinations of the AU obviated the need for transit measurements. By studying the 1999 transit of Mercury, using observations taken from space with NASA's Transition Region and Coronal Explorer (TRACE), we have fully explained Mercury's black-drop effect, with contributions from not only the telescope's point-spread function but also the solar limb darkening. Since Mercury has no atmosphere, we have thus verified the previous understanding, often overlooked, that the black-drop effect does not necessarily correspond to the detection of an atmosphere. We continued our studies with observations of the 2004 transit of Venus with the TRACE spacecraft in orbit and with ground-based imagery from Thessaloniki, Greece. We report on preliminary reduction of those data; see http://www.transitofvenus.info for updated results. Such studies are expected to contribute to the understanding of transits of exoplanets. Though the determination of the Astronomical Unit from studies of transit of Venus has been undertaken only rarely, it was for centuries expected to be the best method. The recent 8 June 2004 transit of Venus provided an exceptionally rare opportunity to study such a transit and to determine how modern studies can explain the limitations of the historical observations.

1. History

With *De Revolutionibus* of Nicolaus Copernicus, published in 1543, our modern solar-system came into consideration. From Copernicus's famous diagram, it was clear that only Mercury and Venus have orbits interior to that of Earth, with the result that only Mercury and Venus could transit across the sun's disk. The Copernican system reached England in 1576 with the appendix that Thomas Digges wrote to the *Prognostication Everlasting* book written by his father, Leonard Digges. This edition marked the first appearance in English of a Copernican diagram (Fig. 1).

The Mars data of Tycho Brahe, in the hands of Johannes Kepler, led to Kepler's laws of planetary orbits, which we use today to understand the orbits of not only the planets around the sun but also double stars and extra-solar planets (exoplanets). In 1609, in his *Astronomia Nova*, Kepler advanced (though not explicitly) his first two laws: (1) that the planets orbit the sun in ellipses, with the sun at one focus; and (2) that the line joining the sun and a planet sweeps out equal areas in equal times, which we now recognize as a consequence of conservation of angular momentum. Most important for the story of the determination of the Astronomical Unit is Kepler's third law, advanced in his *Harmonices Mundi* of 1619. This law holds that the squares of the periods of the planets are proportional to the cubes of the semimajor axes of their orbits. For this work, we will take the Astronomical Unit to be the average distance from the Earth to the sun and equivalent to the semimajor axis of the Earth's orbit; a technical discussion of the definition of the Astronomical Unit is given in the review by Standish (these proceedings).

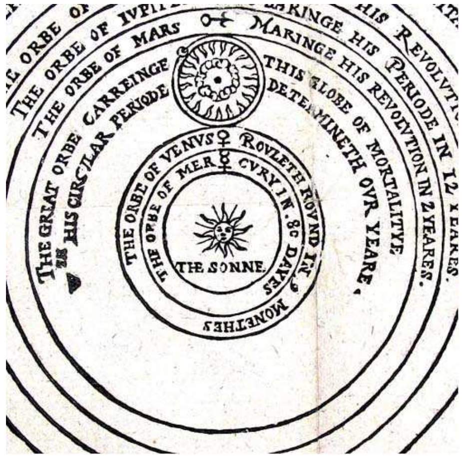


Figure 1. The first English-language Copernican diagram, from a 1596 printing of the *Prognostication Everlasting* of Leonard Digges with the Copernican appendix by Thomas Digges.

Though Kepler's third law provided the proportions of orbital semimajor axes – with that of Venus being about 70%, and that of Mars about 150%, that of Earth – no actual distances were known. Among other consequences of this deficiency was that the physical diameters of any of the planets or of the sun was not known. For example, Digges's book showed Venus much smaller than Earth.

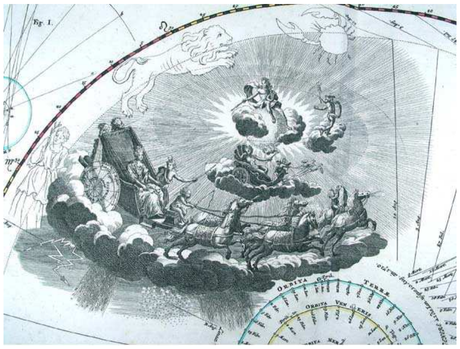
Kepler's *Rudolphine Tables* (1627) was not an ephemeris; that is, it did not make specific predictions, though it provided tables to allow such predictions to be made. The story is told elsewhere in these proceedings of how Jeremiah Horrocks himself predicted and observed the 1639 transit of Venus, and brought his friend William Crabtree also into the sole pair of observers of that event.

The suggestion by Edmond Halley (1716) that transits of Venus can be used to determine the distance to Venus from its parallax led to dozens of international expeditions for the 1761 transit. Halley's method required accurate measurement of the duration of the transit from a given location in order to determine the length of the chord (Fig. 2). He thought that such determination could be made to approximately one second of time. But Bergman (1761), in observing the transit, reported that a ligature joined the silhouette of Venus to the dark background exterior to the sun (Fig. 3). This dark "black drop" meant that observers were unable to determine the time of contact to better than 30 s or even 1 min. The black-drop effect thus led to uncertainty in Venus's parallax, and thus the sun's parallax, and thus the Astronomical Unit.

Of the dozens of expeditions that went all over the world to observe the transit from different latitudes, perhaps the best known was that of James Cook (Fig. 4; see Orchiston, these proceedings). The British Admiralty hired the young lieutenant, gave him a ship, and sent him to Tahiti for the observations. His later peregrinations around New Zealand and the eastern coast of Australia are thus spinoffs of astronomical research. On board was an astronomer, Charles Green (a descendant of whose was excited, just after the 2004 transit, to hear her ancestor's work still being discussed at a site on a Greek island). Cook's and Green's observations (Fig. 5) clearly show the black-drop effect (Cook & Green, 1771).

Cook (1768–71) reported in his *Journal*:

> This day prov'd as favourable to our purpose as we could wish, not a Clowd was



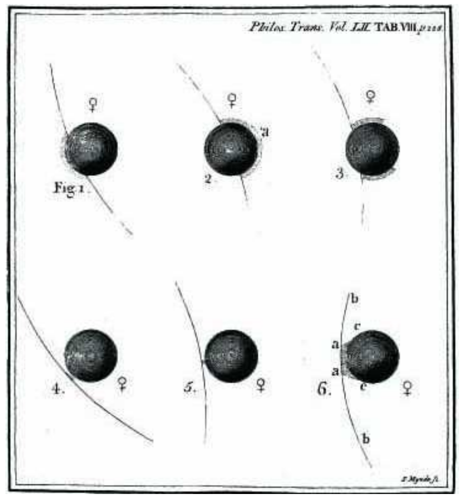


Figure 2. (left) The path of Venus across the face of the sun at the transit of 1761, from a book by Johann Doppelmayr (1742).

Figure 3. (right) The black-drop effect, as reported at the transit of 1761 by T. Bergman (1761) ©Royal Society

Figure 4. Captain James Cook, shown in a statue in the garden of his parents' house, which had been moved from England to a public park in Melbourne, Australia.

to be seen the whole day and the Air was perfectly clear, so that we had every advantage we could desire in Observing the whole of the passage of the Planet Venus over the Suns disk: we very distinctly saw an Atmosphere or dusky shade round the body of the Planet which very much disturbed the times of the Contacts particularly the two internal ones. Dr Solander observed as well as Mr Green and my self, and we differ'd from one another in observeing the times of the Contacts much more than could be expected. Mr Greens Telescope and mine were of the

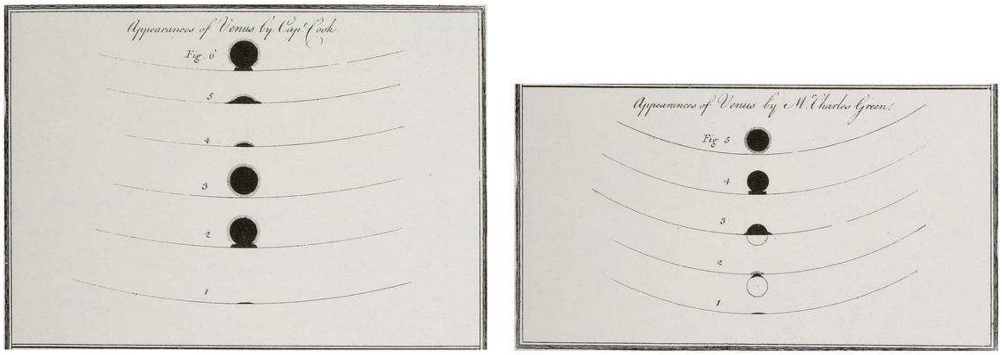


Figure 5. The 1769 black-drop observations of James Cook (left) and Charles Green (right) (Cook & Green 1771). ©Royal Society

> same Mag[n]ifying power but that of the Dr was greater than ours. It was ne[a]rly calm the whole day and the Thermometer expose'd to the Sun about the middle of the Day rose to a degree of heat we have not before met with.

So Cook's report both correctly mentioned the existence of an atmosphere around Venus, which had been discovered at the 1761 transit, but then incorrectly attributed the inaccuracy in his ability to time the transit's contacts to that atmosphere.

The next pair of transits wasn't for another 105.5 years. The 1874 transit was clearly observed in Australia. The black-drop effect showed well and was widely reported and drawn (Fig. 6). Janssen attempted to photograph it with a "photographic revolver," a revolving plate of which three French examples (Flammarion, 1875) are preserved in France, and one example of a British derivative remains on display at the Sydney Observatory. Unfortunately, the widely-reproduced plate of his observations is not of the actual transit but rather of a previous test (Fig. 7), as shown by Launay & Hingley (2005). They showed that it was first published in 1891 and then reproduced in Janssen's *Oeuvres Scientifiques* of 1929.

The newfangled photography turned out not to be of use in resolving the problem of the black-drop effect. In general, the 19th-century techniques did not provide an advance over the 18th-century techniques (Meadows 1974). Some photographs survive from the 1882 transit expeditions (Fig. 8).

Many historic images of the black-drop effect appear at Chuck Bueter's Website at http://www.transitofvenus.org/blackdrop.htm. Pasachoff (2003b, 2004) reviewed recent books that discussed the historical transits of Venus.

2. The 1999 transit of Mercury

The rare transit of Venus expected in 2004 was anticipated (Pasachoff 2000, 2002, 2003a; Pasachoff & Filippenko 2004) as a remarkable event. A paper delivered before the History of Astronomy Division of the American Astronomical Society (Schaefer 2001) led us to realize the utility of existing observations of the 1999 Mercury transit with NASA's Transition Region and Coronal Explorer (TRACE) for analyzing the problem of the black-drop effect. Schaefer reported that most of the citations, even current ones, incorrectly attributed the black-drop effect to Venus's atmosphere. But TRACE was above the Earth's atmosphere and Mercury has essentially no atmosphere, so any Mercurian black drop could not arise from atmospheric factors.

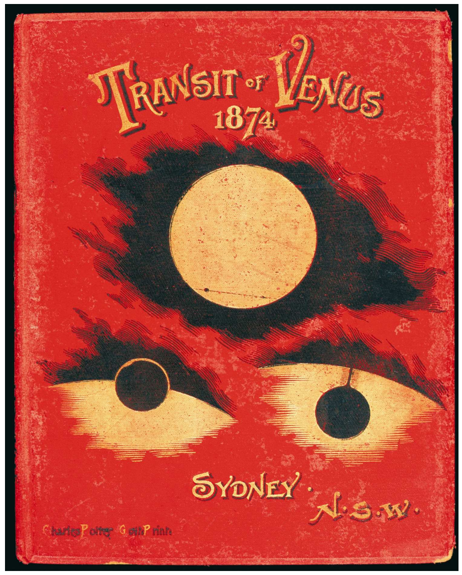


Figure 6. The cover of *Transit of Venus 1874* by Henry Chamberlain Russell, Government Astronomer for New South Wales, Australia. (Courtesy of Sydney Observatory, part of the Powerhouse Museum)

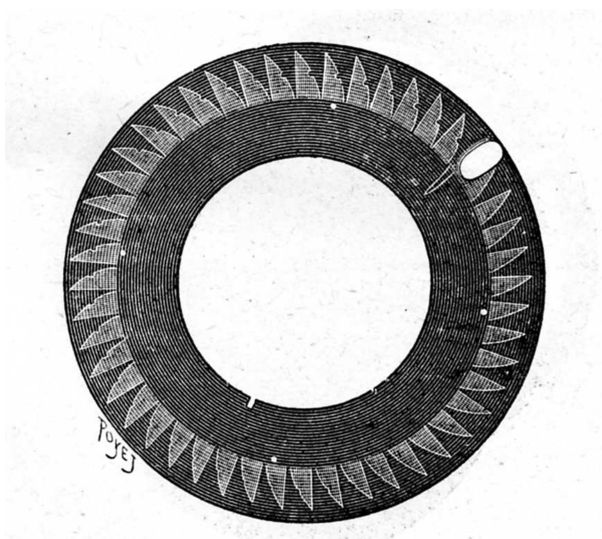


Figure 7. Engraving made in the 19th century from one of Janssen's tests. (Courtesy of Françoise Launay, Observatoire de Paris, Section de Meudon)

The 1999 Mercury transit was widely observed, including high-resolution observations from the Swedish Solar Telescope on La Palma, Canary Islands, Spain (Fig. 9); New Jersey Institute of Technology's Big Bear Solar Observatory; the University of Hawaii's Mees Solar Observatory; and the National Solar Observatory's Global Oscillation Network Group's telescopes around the world (GONG).

We used the white-light ($0.2 - 1.0\,\mu$m) imagery from TRACE, though various ultraviolet/extreme ultraviolet (UV/EUV) data also exist. TRACE provides steady seeing with a temporally stable point-spread function of $1''$ resolution, sampled with $0\farcs5$ pixels.

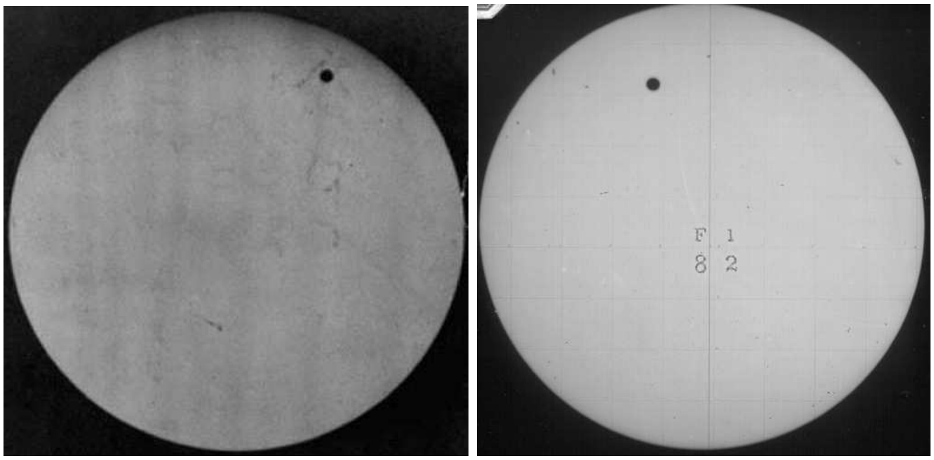


Figure 8. (left) The transit of Venus photographed at Vassar College by Prof. Maria Mitchell and her students. (Courtesy of Special Collections, Vassar College Library). (right) The transit of Venus from one of the U.S. Naval Observatory expeditions, with a superimposed grid to aid in data reduction. (U.S. Naval Observatory)

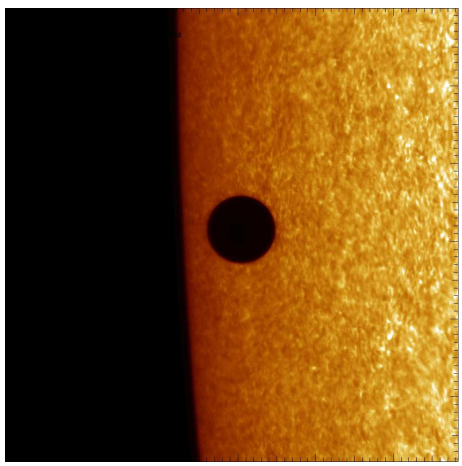


Figure 9. The 1999 transit of Mercury, photographed from the Swedish Solar Telescope. (Royal Swedish Academy of Sciences)

The results show a slight black-drop effect at ingress (Fig. 10); egress was not observed. Wittmann (1974) had shown that a black drop for a Mercury transit could be the result of blurring in the Earth's atmosphere, but we were observing from space.

We calibrated the CCD data in standard ways, and then applied additional corrections to remove pattern noise and other low-level effects (Fig. 11, left). The result clearly showed the black-drop effect (Fig. 11, right). Extensive modeling revealed that the point-spread function was not sufficient to explain the observed form of the black drop, and that the effect of the solar limb darkening had to be included (Fig. 12). Though the possibility of such a contribution had been alluded to by others (Sveshnikov & Sveshnikov 1996), in a conference proceedings of which we were unaware, we provided the first numerical model of observational data proving that the contribution indeed existed. Removing the two contributions left a circularly symmetric silhouette for Mercury, indicating that all causes of a measurable black-drop effect were accounted for (Fig. 13). We discussed our

Figure 10. Series showing the evolution of the black-drop effect at ingress during the 1999 transit of Mercury, observed from NASA's Transition Region and Explorer (TRACE) spacecraft. (Schneider, Pasachoff, and Golub/LMSAL and SAO/NASA)

results at meetings of the Division of Planetary Sciences of the American Astronomical Society (Schneider, Pasachoff & Golub 2001), the General Assembly of the International Astronomical Union (Schneider, Pasachoff, & Golub 2003), and the History of Astronomy Division of the American Astronomical Society (Pasachoff, Schneider, & Golub 2004). Our refereed paper on the subject appeared in *Icarus* (Schneider, Pasachoff, & Golub 2004b).

Data acquired by TRACE from the 2003 transit of Mercury were downlinked in compressed format that did not allow us to carry out the type of data reduction we had previously made.

3. The 2004 transit of Venus

We observed the 8 June 2004 transit of Venus with the TRACE satellite, following a detailed coordinated observing plan developed in collaboration with the TRACE team. The plan included the timing and cadence of the observations, the filter interleaving, the pointing of the spacecraft, and the data transmission method. To obtain ground-based observations for comparison, we observed from the Aristotelian University of Thessaloniki, Greece (http://www.astro.auth.gr), using especially their 20-cm f/15 refractor as well as a host of other telescopes and cameras. The whole duration of the transit, including both black drops, was to be visible from both the spacecraft and Greece. We also arranged for a colleague, Steven Souza, to observe third and fourth contacts with our Carroll spar 12.5-cm f/14 solar refractor at Williams College, Williamstown, Massachusetts (http://www.williams.edu/astronomy).

Two weeks prior to the transit, one of us had observed the solar chromosphere with the

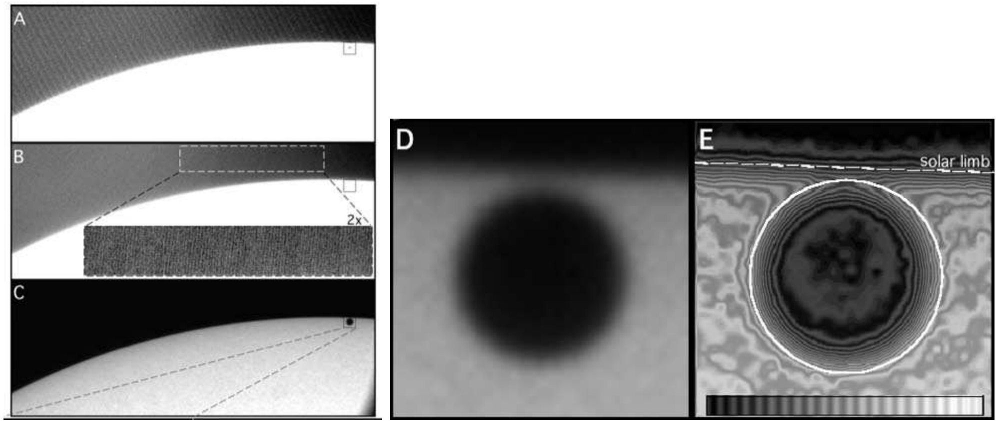


Figure 11. (left) Modeling of effects to improve the data quality of TRACE images from the 1999 transit of Mercury, observed from NASA's Transition Region and Explorer (TRACE) spacecraft. (right) The black-drop effect on a TRACE image from the 1999 transit of Mercury, observed from NASA's Transition Region and Explorer (TRACE) spacecraft. It is shown both as an image and as isophotes. (Schneider, Pasachoff, and Golub/LMSAL and SAO/NASA)

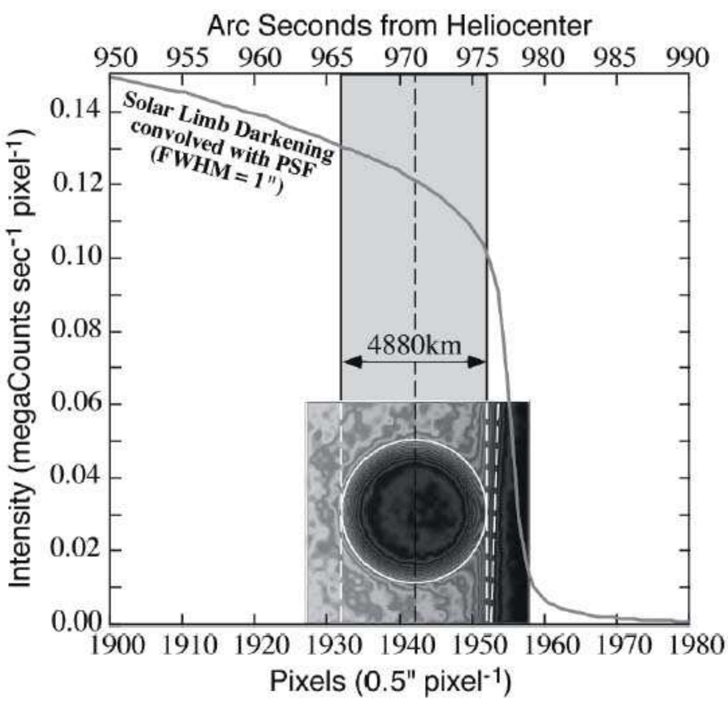


Figure 12. Modeling the contributions of the telescope's point-spread function and of solar limb darkening on TRACE images from the 1999 transit of Mercury, observed from NASA's Transition Region and Explorer (TRACE) spacecraft. (Schneider, Pasachoff, and Golub/LMSAL and SAO/NASA)

Swedish Solar Telescope of the Royal Swedish Academy of Sciences. This 1-m telescope is located on La Palma. We grew to understand the workings, the variability of the seeing quality – which at its best is unsurpassed in the world – and the need for a discrete, dark object in order to make the adaptive optics function consistently. Adaptive optics, made

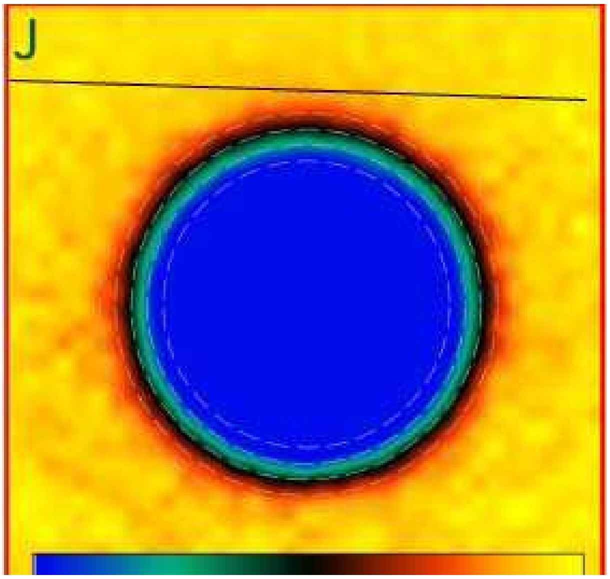


Figure 13. A TRACE image from the 1999 transit of Mercury, observed from NASA's Transition Region and Explorer (TRACE) spacecraft. The effect of the telescope's point-spread function and the solar limb darkening have been removed, revealing a symmetric Mercury silhouette. The position of the solar limb is marked. (Schneider, Pasachoff, and Golub/LMSAL and SAO/NASA)

possible with their Wave Front Sensor, was achieved some of the time during the transit. One of their images from the transit of Venus appears in Fig. 14. Dan Kisselman of the Royal Swedish Academy of Sweden supervised the transit observations, and arranged for a new spectrograph to be installed and to operate.

Figure 14. Venus just after second contact in a ground-based image taken with the 1-m Swedish Solar Telescope on La Palma. The solar limb is at the top; the cicular arcs merely mark the edge of the field-of-view. (Royal Swedish Academy of Sciences)

We are very pleased with the series of transit of Venus observations obtained to our specifications with the TRACE satellite. Our data reduction significantly improves upon the image contrasts obtained with standard image processing (e.g., as shown on the TRACE website) by modeling and removing instrumentally ghosted and scattered light. We were able to follow the evolution of visibility of Venus's atmosphere at both ingress (Fig. 15, left) and egress with views up to a full Venus diameter from the solar limb. Presentation of the observations with a different stretch shows images more suitable for our study of the black-drop effect (Fig. 15, right). Our continuing data reduction appears on the Results page accessible from http://www.transitofvenus.info. These data and other images from our expedition are accessible through

http://www.williams.edu/astronomy/eclipse

One of our preliminary isophotal images of the Venus transit, with a limb darkening function removed, appears as Fig. 16.

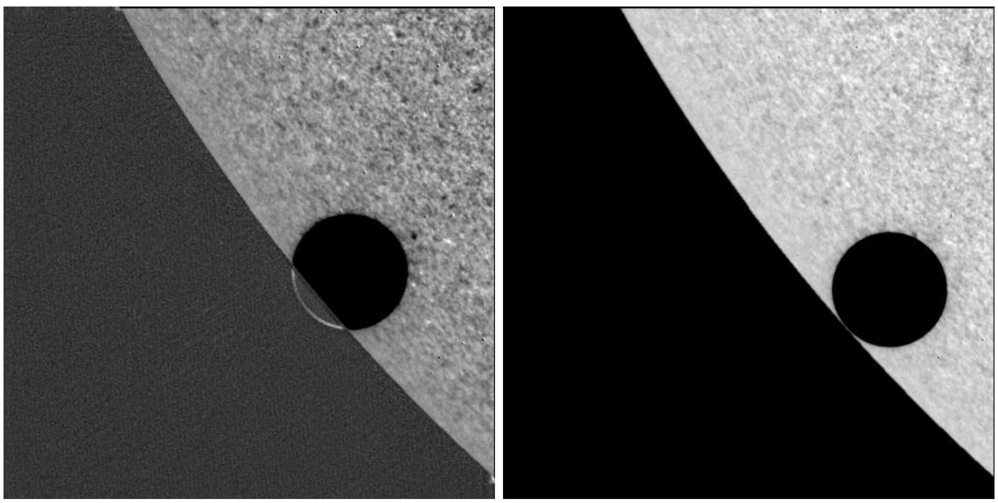


Figure 15. (left) Venus's atmosphere, seen between first and second contacts on 8 June 2004. (right) Venus in transit, seen just after second contact on 8 June 2004; from a series of images processed by us from TRACE data. (Schneider/Pasachoff/LMSAL/SAO/NASA)

Reports from observers all over the world indicate that the black-drop effect was less prominent than had been expected, though such comments had also appeared in reports of the 19th-century transits (Launay & Hingley 2005). Since prior knowledge showed that the black-drop effect was not intrinsic to Venus but was rather a combination of instrumental effects and effects to some degree in the atmospheres of Earth, Venus, and Sun, it is no surprise that the better telescopes we have now, since the time of Captain Cook, provide cleaner images and potentially less black drop. Some images posted on the Web, presumably with telescopes of lesser optical quality and/or worse seeing, indeed show the typical shape of the black drop. Some of our data from the 20-cm ground-based telescope in Greece clearly show the existence of a black-drop effect (Fig. 17), and we are making animations to follow its evolution. We can also follow the formation and evolution of a black-drop effect with scanned photographic observations obtained with a 1600-mm Nikon lens on slide film. We anticipate detailed data reduction of the CCD and photographic data.

Acknowledgements

The 2004 transit of Venus expedition was supported by a grant from the Committee

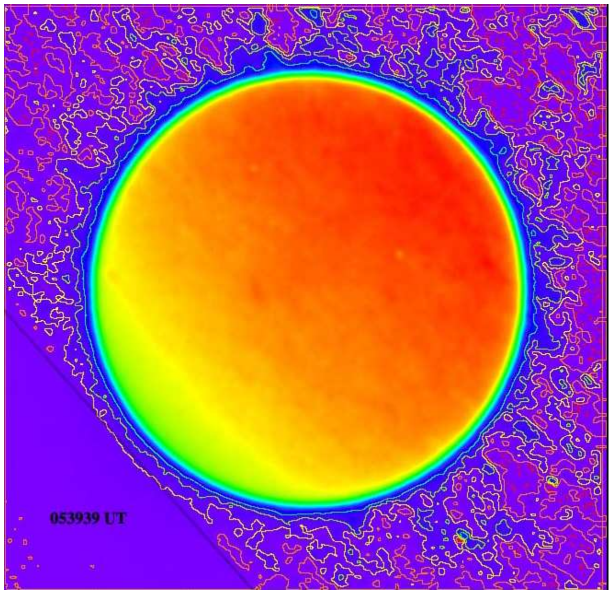


Figure 16. Isophotes on an image processed by us from TRACE data with a limb-darkening function removed. (Schneider/Pasachoff/LMSAL/SAO/NASA)

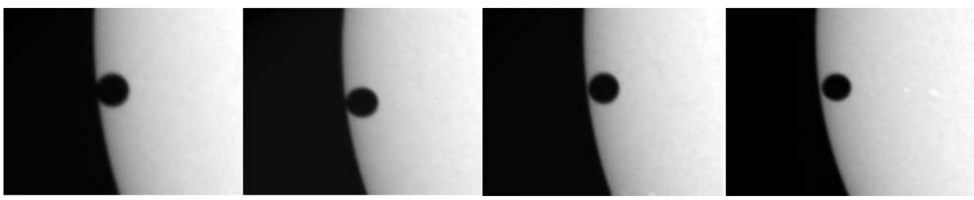


Figure 17. Images taken by the Williams College Expedition with the Aristotelian University of Thessaloniki's 20-cm refractor and an Apogee CCD, operated by Bryce Babcock, processed by Kayla Gaydosh with the assistance of Steven Souza.

for Research and Exploration of the National Geographic Society. We also acknowledge the support for Joseph Gangestad's participation from Sigma Xi, the Scientific Research Society. The previous work on the transits of Mercury was supported in part by NSF grant ATM-000545; Pasachoff's work on eclipses has also been supported in part by the Committee for Research and Exploration of the National Geographic Society. His solar TRACE work is supported by NASA Guest Investigator grant NNG04GF99G. TRACE is supported by a NASA/GSFC contract to the Lockheed Martin Corp. Extensive use of analysis software developed by the NICMOS IDT under NASA grant NAG 5-3042 is acknowledged.

We thank especially Karel Schrijver at Lockheed Martin Solar and Astrophysics Laboratory and his colleagues there, and Edward DeLuca at the Harvard-Smithsonian Center for Astrophysics, for their collaboration in obtaining the transit of Venus observations with data recording and transmission to our specifications and requests.

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