

THE 1761 DISCOVERY OF VENUS' ATMOSPHERE: LOMONOSOV AND OTHERS

Vladimir Shiltsev

Fermilab, PO Box 500, Batavia, Illinois 60510, USA.

E-mail: shiltsev@fnal.gov

Abstract: Russian polymath Mikhail Vasil'evich Lomonosov claimed to have discovered the atmosphere of Venus during the planet's transit over the Sun's disc in 1761. Although several other astronomers observed similar effects during the 1761 and 1769 transits, Lomonosov's claim for priority is the strongest as he was the first to publish a comprehensive scientific report, and the first to offer a detailed explanation of the aureole around Venus at ingress and egress, which was caused by refraction of the sunlight through Venus' atmosphere. His observations, moreover, were successfully reconstructed experimentally using antique telescopes during the 2012 transit. In this paper we review details of Lomonosov's observations (which usually are poorly covered by commentators and often misunderstood); compare other reports of the eighteenth century transit observations, and summarize their findings in a comprehensive table; and address recent calls to reconsider Lomonosov's priority. After reviewing the available documentation we conclude that everything we learned before, during and after the twenty-first century transits only supports further the widely-accepted attribution of the discovery of Venus' atmosphere to Lomonosov.

Keywords: Lomonosov, atmosphere of Venus, transits of Venus, experimental replication

1 INTRODUCTION

Venus was the first extraterrestrial body (other than the Sun) that was proven to have a detectable atmosphere. The discovery was made by the Russian polymath Mikhail Vasil'evich Lomonosov (1711–1765; Menshutkin, 1952; Shiltsev, 2012a; 2012c), who observed the 1761 transit of Venus from St. Petersburg, detecting a luminous arc around Venus at egress, which led him to realize that it was caused by refraction of the sunlight through the planet's atmosphere. Lomonosov promptly reported his results at length, in Russian and in German, in two different scientific papers (Lomonosov, 1761a; 1761b), concluding that

... the planet Venus is surrounded by a significant airy atmosphere similar to (if not even greater than) that which surrounds our terrestrial globe. (Lomonosov, 1761a; here and in the remainder of this paper, the English translations are after Shiltsev 2012b, unless otherwise stated).

Since the late nineteenth century, Lomonosov's priority has been widely accepted (e.g., see Bond, 2007: 46; Lomb, 2011: 190-191; Lur-Saluces, 1933: 297; Lyubimov, 1855: 30; Maor, 2000: 90; Marov and Grinspoon, 1998: 16; Maslikov, 2007; Moore, 1961: 84-87; Perevozchikov, 1865; Schilling, 2011: 42; Sharonov, 1952a; Shirley and Fairbridge, 1997: 393; Smith, 1912; Tchenakal, 1961; Wulf, 2012: 75-77). However, Pasachoff and Sheehan (2012a) recently expressed skepticism about this discovery in this journal, questioning whether Lomonosov could have detected Venus' atmosphere with his telescope, and calling for a re-examination of the circumstances of the discovery.

In this paper we describe Lomonosov's findings and compare them with similar observations of the eighteenth-century transits; review

the discussions on the discovery of the atmosphere during the nineteenth and twentieth centuries; critically study the arguments presented by Pasachoff and Sheehan (2012a); and discuss the results of the successful experimental reconstruction of Lomonosov's discovery during the 2012 transit of Venus.

2 LOMONOSOV'S OBSERVATIONS DURING THE 1761 TRANSIT OF VENUS

Lomonosov observed the transit of Venus on 26 May (old style; 6 June, new style), 1761, from his estate in St. Petersburg (modern address: Bolshaya Morskaya, 61) at latitude 59° 55' 50" N and longitude 30° 17' 59" E (Chenakal, 1957a). He used "... a 4½ ft. long telescope with two glasses ... [and a] ... not-so-heavily smoked glass ..." as a weak solar filter (Lomonosov, 1761a: 7). The reason for the filter was that he

... intended to observe the beginning and the end of the phenomena only and then to use the power of the eye, and give [his] eyes a respite for the rest of the transit. (Lomonosov, *ibid.*).

His original telescope was destroyed during WWII, a victim of the heavy bombardment that leveled Pulkovo Observatory and the suburbs of St. Petersburg. For a long time there was uncertainty regarding the type of telescope Lomonosov used, as evidenced by the commentary in the standard edition of Lomonosov's works (Vavilov and Kravets, 1950-1983). Although some hints were given by Melnikov (1977) back in the 1970s, only recently has research uncovered a pre-WWII publication (Nemiro, 1939) in which a witness describes several notable antique telescopes in the Pulkovo museum collection, which was established more than fifty years prior to that date:

... the most numerous group of tools are the instruments ordered to observe the transit of Venus across the solar disk in 1761 and 1769. This group includes achromatic telescopes by Dollond, the reflectors by Short of the Gregorian design with lens-heliometers, and quadrants by Sisson. One of these Dollond refractors was used by famous Lomonosov to make the biggest discovery – he discovered the existence of an atmosphere of Venus during its passage through the disk of the Sun in 1761. (Koukarine et al., 2012; our English translation).

The full list of old astronomical instruments in the collection of the Pulkovo Observatory compiled in the late nineteenth century includes two Dollond achromats of 4½ feet length dating to Lomonosov's time, one with an objective of 2.1 inches aperture and another with a 2¾-inch objective (Struve, 1886).

In 1761, the achromatic refractors just recently invented by the renowned English optician John Dollond (1706–1761) most distinctively differed from the old, non-achromatic refractors by having the second lens ('glass') in the objective, hence the reference to "two glasses" in Lomonosov's description. Given that Lomonosov's transit drawings (see Figure 1) are reversed, one can conclude that his telescope was a 4.5-foot reversed image astronomical refractor, with a two-lens achromatic objective made by John Dollond (Petrunin, 2012).

Pasachoff and Sheehan's (2012a: 5) reference to Lomonosov's refractor as "non-achromatic" is therefore incorrect. Furthermore, Lomonosov's Dollond achromat was a much more serious scientific instrument than one recent translator's careless rendering as "... a sort of spy-glass ..." would suggest (Marov, 2005: 213). The outstanding quality of the eighteenth-century Dollond achromats was specifically noted by observers of the 2012 transit of Venus who used antique telescopes (e.g., see Kukarin et al., 2013). Some of the Dollond telescopes similar to the one used by Lomonosov have been analyzed using modern optical techniques and have demonstrated excellent performance (e.g., see Petrunin, 2012). ZYGO-type interferometric measurements of the 4.5-ft Dollond achromat employed for the replication of Lomonosov's discovery gave the following results (with reference to the diffraction-limited optical parameters in parenthesis): peak-to-peak wave front error of 1/3.9 wavelength (1/4 or less); rms error of the wave front of 1/21 waves (1/14 or less); and a Strehl ratio of 0.916 (0.8 or more). Consequently, Koukarine et al. (2012) concluded: "... the optics of this telescope made almost two and half centuries ago are of very good quality even by today's standards."

During his observation of the 1761 transit of

Venus Lomonosov reported three different types of phenomena:

1) phenomenon *PI* = a 'blister' or 'bulge' which lasted for a few minutes after the 3rd contact (this is illustrated in Lomonosov's Figures 3, 4 and 5, and at point A in Figure 1—see our Figure 1). Lomonosov's Figures 3-5 indicate that the 'blister'-'bulge' at 3rd contact (which we will henceforth refer to as an 'arc') started to grow from the beginning of egress (egress phase 0), when Venus was fully on the Sun's disc, all the way to an egress phase of about 0.1 (where 1/10th of Venus' diameter was external to the solar photosphere). Therefore, it lasted for a few minutes before it disappeared.

2) phenomenon *PII* = the 'blurriness' of the solar limb at the time of 1st contact (illustrated in Lomonosov's Figure 1 at point B), and a similar 'blurriness' at 4th contact.

3) phenomenon *PIII* = a "hair-thin bright radiance" close to 2nd contact, which lasted about a second (this was not illustrated).

It ought to be noted that Lomonosov concluded the existence of an atmosphere of Venus on the basis of only two out of the three different phenomena observed by him, namely *PI* and *PII* above, leaving the "hair-thin bright radiance" near the 2nd contact (*PIII*) out of the argument.

The *Chronicles of the Life and Work of M.V. Lomonosov* (Chenakal, et al., 1961), which present all the known documented facts of his life, indicate that Lomonosov commenced the writing of his observational report the day after the transit. He submitted his 17-page long paper, written in Russian and titled "The appearance of Venus on the Sun, observed at the St. Petersburg Imperial Academy of Sciences on May 26, 1761" (Lomonosov, 1761a) for publication on 4 July 1761 (o.s.), and 250 copies were published by the St. Petersburg Imperial Academy of Sciences on 17 July 1761 (according to the records of the Russian National Library)—and they were fully distributed within a few months (Tyulichev, 1988). It is of interest to note that pages 10-16 of the published report are devoted to a defense of the heliocentric hypothesis and a discussion of the possibility of life on Venus in light of the discovery of its atmosphere—a subject of wide scientific interest at the time (e.g., see de Fontenelle, 1686). A German translation of the Russian paper (Lomonosov, 1761b) was made shortly after (presumably by Lomonosov himself), and 250 copies were printed in August 1761, destined for wide distribution abroad (Sharonov, 1952b; Tyulichev, 1988). The Russian and German texts are essentially identical, differing by only eight insignificant words and phrases (Chenakal and Sharonov, 1955). Four English translations of the nucleus of Lomonosov's Russian paper (Lomonosov, 1761a: 7-9)

have been published to date. Meadows (1966) is the closest to the original, and has just a few insignificant omissions. Marov (2005) contains a number of errors and deviations from the original text, although none of these alters the major content and conclusions of the original; however, Marov's version does provide a useful discussion of the historical background of the 1761 observations made at St. Petersburg, as well as references to known drafts and preparatory documents that led to Lomonosov's published report. The recent paper by Pasachoff and Sheehan (2012a) offers a relatively good translation, with few deviations from the original text, but unfortunately the commentary is marked by several important misconceptions and misinterpretations (see Section 5 below). The most recent, complete and heavily-annotated translation by the present author (Shiltsev, 2012b) is, I believe, the closest 'word-for-word' rendering, and is free from the deficiencies of the three preceding translations.

Lomonosov's transit paper was included in all the major editions of his *Complete Works* issued by the St. Petersburg and the USSR-Russian Academy of Sciences, e.g., in those published in 1803, 1891-1948, 1950-1983 and 2011. The most complete one (Vavilov and Kravets, 1950-1983) also contains five related notes, letters and drafts and extended editorial commentaries. The transit paper itself, particularly its scientific (physics) content and historical importance have been discussed in great detail in several publications by practicing astronomers and historians of science (see the following sections).

In his own words (cf. Shiltsev, 2012b):

... Collegiate Councilor and Professor Lomonosov kept an alert watch mostly for physical observations at his place, using a 4½ ft.-long telescope with two glasses. The tube had attached a lightly-smoked glass, for he intended to observe the beginning and the end of the phenomenon only and then to use the power of the eye, and give [his] eyes a respite for the rest of the transit.

Having waited for Venus to appear on the Sun for about forty minutes beyond the time prescribed in the ephemerides, [he] finally saw that the Sun's edge at the expected entry became indistinct and somewhat effaced, although before [it] had been very clear and equable everywhere (see B, Fig. 1); however, not seeing any blackening and thinking that his tired eyes were the cause of this blurring, [he] left the eyepiece. After a few seconds, [he] took a glance through the eye-piece and saw that in the place where the Sun's edge had previously appeared somewhat blurred, there was indeed a black mark or segment, which was very small, but no doubt due to the encroaching Venus. Then [he] watched attent-

ively for the entry of the other (trailing) edge of Venus, which seemed to have not yet arrived, and a small segment remained beyond the Sun. However, suddenly there appeared between the entering trailing edge of Venus and the solar edge, a hair-thin bright radiance separating them, so that the time from the first to the second was no more than one second.

During Venus' egress from the Sun, when its front edge was beginning to approach the solar edge, and was (just as the naked eye can see) about a tenth of the diameter of Venus, a blister [pimple] appeared at the edge of the Sun (see A, Fig. 1), which became more pronounced as Venus was moving closer to a complete exit (see Fig. 3 and Fig. 4). LS is the edge of the Sun, mm is the Sun bulging in front of Venus. Soon the blister disappeared, and Venus suddenly appeared with no edge

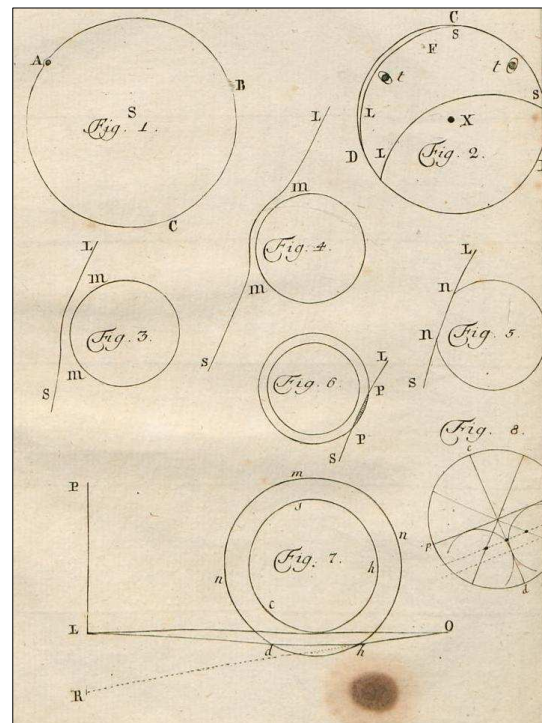


Figure 1: Lomonosov's drawings of the sequence of phenomena during the phases of ingress and egress of the 1761 transit of Venus (after Lomonosov, 1761a: 17).

(see Fig. 5); nn is a segment, though very small, but distinct.

Complete extinction or the last trace of the trailing edge of Venus on the Sun at its very emergence followed after a small break and was characterized by a blurring of the solar edge.

While this was happening, it clearly appeared that as soon as Venus moved away from the axis of the tube and approached the edge of the field of view, a fringe of colors would appear due to the refraction of rays of light, and its [Venus'] edges seemed smeared the further [it] was from the axis X (Fig. 2). Therefore, during the entire observation the tube was permanently directed in such a way that Venus

was always in its center, where its [Venus'] edges appeared crisply clear without any colors.

From these observations, Mr. Councilor Lomonosov concludes that the planet Venus is surrounded by a significant atmosphere of air similar to (if not even greater than) that which surrounds our terrestrial globe. This is because, in the first place, the loss of clearness in the [previously] tidy solar edge B just before the entry of Venus on the solar surface indicates, as it seems, the approach of the Venusian atmosphere onto the edge of the Sun. The clarification of this is evident in *Fig. 6*; LS is the edge of the Sun, PP is a portion of Venus' atmosphere. At the time of Venus' egress, the contact of its front edge produced the bulge. This demonstrates nothing but the refraction of solar rays in the atmosphere of Venus. LP is the end of the diameter of the visible solar surface (*Fig. 7*); *sch* is the body of Venus; *mnn* is its atmosphere; LO is the [light] ray propagating from the very edge of the Sun to the observer's eye tangential to the body of Venus in the case of the absence of an atmosphere. But when the atmosphere is present, then the ray from the very edge of the Sun *Ld* is refract-

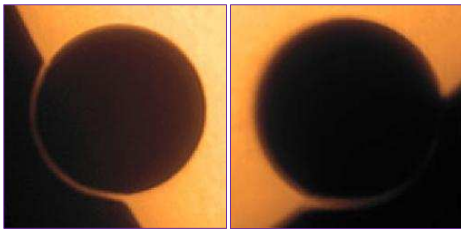


Figure 2: Photographs of the ingress (left) and egress (right) of Venus taken by Lorenzo Comolli at Tradate, Italy on 8 June, 2004 (after Comolli, 2004).

ed towards the perpendicular at *d* and reaches *h*, thus, being perpendicularly refracted, it arrives at the observer's eye at O. It is known from optics that the eye sees along the incident line; thus, the very edge of the Sun L, due to refraction, has to be seen in R, along the straight line OR, that is beyond the actual solar edge L, and therefore the excess of the distance LR should project the blister on the solar edge in front of the leading edge of Venus during its egress.

Fig. 8 (in Figure 1) illustrates the method used by A.D. Krasilnikov and N.G. Kurganov at the St. Petersburg Academy Observatory (Chenakal, 1957b) to measure the minimal distance from Venus to the center of Sun and the diameter of Venus.

Lomonosov's *Complete Works* also contain "*Preparatory Notes for the "Appearance of Venus on the Sun..."*" which add a little to the description of phenomenon *PIII*:

... then suddenly there appeared between the entering trailing edge of Venus and the solar edge, a hair-thin bright part of the Sun, so that the time from the first to the second was no more than one second. (Vavilov and Kravets, 1950-1983(4): 389-390; my English translation).

As we will see in the following sections, observations of atmospheric effects similar to Lomonosov's were reported by many astronomers during the transits of the eighteenth, nineteenth and twenty-first centuries. For example, Figure 2 shows photographs taken in Italy with a modern 20-cm Schmidt-Cassegrain telescope and a digital camera during the 2004 transit (Comolli, 2004). Characteristic features of the luminous arc (*PI*) similar to what was drawn in Lomonosov's *Fig. 4* are clearly seen—the arc is thinner and fainter in the middle, and wider and brighter at the ends approaching the Sun's limb. The dimmer part of the arc may not appear well marked, and can assume the form of a 'whisker' (an incomplete arc), as in Figure 2 (right). Recent discussion about the formation of the arc and modeling of its appearance (see García-Muñoz and Mills, 2012) is fully consistent with all of these observations. Replication of Lomonosov's discovery with antique refractors during the 2012 transit resulted in similar observations (see Section 6 for details).

Most commentators on Lomonosov's report agree that he correctly and fully described the physical mechanism of refraction underlying his observations, and that he came to the right conclusion: that Venus possesses a dense atmosphere. It fully follows the basics of the theory of refraction which he had earlier studied because of its implications for the accuracy of maritime navigation, e.g., "... the rate of refraction corresponds to the transparent matter, i.e. air, thus the amount of matter that a ray propagates is the rate of refraction." (Lomonosov, 1759).¹ Only in the mid-1960s did the farsightedness of his assumption that Venus' atmosphere can be even more dense than that of the Earth become clear, when Venus' atmosphere was revealed to be nearly two orders of magnitude thicker than our terrestrial atmosphere (Marov and Grinspoon, 1998).

We also should note how precise, accurate and descriptive Lomonosov's drawings are (see Figure 1). For example, the diameters of the Sun and Venus in his *Fig. 4* differ by a factor of about 32, which is very close to the actual value. As we will see below, not many other observers achieved such accuracy with their drawings.

3 OTHER EIGHTEENTH CENTURY ACCOUNTS OF A VENUSIAN ATMOSPHERE

About two dozen observers of the 1761 transit reported phenomena which were caused by Venus' atmosphere or perceived to be caused by it. Besides the *PI*, *PII* and *PIII* phenomena observed by Lomonosov (that is, the arc or bulge of light over the part of Venus off the Sun during ingress/egress; the 'blurriness' of the sol-

ar limb at the points of external contact; and the "hair-thin bright radiance" close to the points of internal contact), there were observations of a ring (light or dark) around Venus when it was fully on the disc of Sun, which we will classify as phenomenon *PIV*. What follows is a brief overview of the 1761 reports, with the details of their reports of the atmospheric effects. In particular, all known drawings of the *PI* phenomenon are reproduced below. Many more observers in 1769 saw similar effects, but this discussion is limited only to descriptions of those relevant to the discussion in Section 5.

3.1 Observations of a Complete or Partial Arc Around that Part of Venus Which was off the Sun's Disc (*PI*)

A very clear description of the luminous arc around Venus off the Sun's disc during ingress and egress was given by the noted Swedish scientist, Torbern Bergman (1735–1784), who observed the transit from the University of Uppsala. His account, dated 25 August, was read in London at the 19 November 1761 meeting of the Royal Society and was published in the *Philosophical Transactions* ... (Bergman, 1761-1762):

We believe that we saw Venus surrounded by an atmosphere for the following reasons. Namely, before the completion of the ingress, when about a quarter of the diameter of Venus was still beyond the limb of the Sun, the whole of Venus was visible, because the part protruding was surrounded by a feeble light, as shown in Fig. 1 [see Figure 3 here] ... This was observed much more clearly at the egress; for, initially, the part projecting beyond the limb of the Sun was surrounded by a similar, but brighter light. The part *a* (Fig. 2) which was furthest from the Sun became weaker in proportion to the egress of Venus until a stage was reached when only horn-shaped segments could be seen (Figure 3). I continued to observe the light unbroken, however, until the egress of the central point of Venus. (after Meadows, 1966: 120).

Bergman observed with a 21-ft long non-achromatic refractor, but did not specify the filter used. His description of the arc in general matches that of Lomonosov. He noted that in the later phase of egress, the arc had broken into two horn-shaped segments. His drawings show some deficiencies though (see Fig. 3). First of all, the arc is presented equally thick around Venus' circumference, as well as the horns. Secondly, the points of the arc and horns in contact with the Sun's edge are shown as very distinct sharp angles that cannot represent physical reality. Thirdly, the ratio of the diameters of Venus and the Sun as drawn is about 1:10, which is far from the actual ratio of about 1:32. This indicates that the drawing may have

been designed to illustrate qualitative points rather than quantitative conclusions. It is also to be noted that Bergman observed the notorious 'black drop effect' (Schaefer, 2001) shown in his Figs. 4-6. He suggested that it originated from strong refraction of sunlight in Venus' atmosphere (which it has no relationship to), and he mistakenly shows the wrong curvature of the Sun's limb in his Fig. 5. Despite all these deficiencies, there is little doubt that Bergman refers to a true luminous aureole caused by refraction in the atmosphere of Venus, even though he offered no explanation for the phenomenon depicted in his Figs. 1-3.²

In the same volume of the *Philosophical Transactions* another Swede, Pehr W. Wargentin (1717–1783), the Director of Stockholm Observatory and Secretary of the Royal Swedish Academy of Sciences, reported his observations

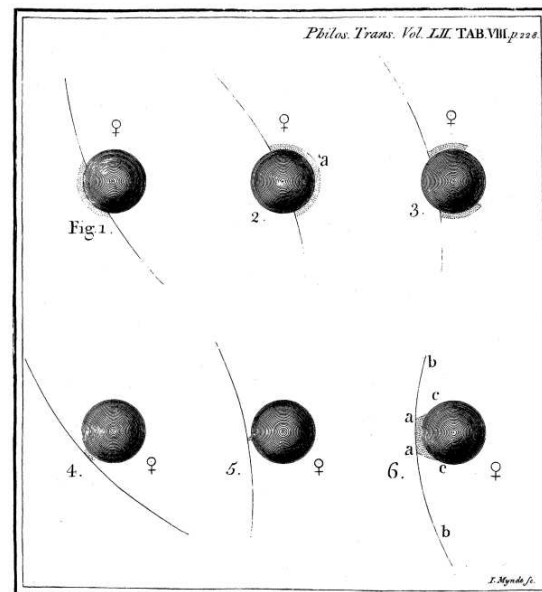


Figure 3: Drawings by T. Bergman showing Venus at ingress and egress (after Bergman, 1761-1762: 223).

(Wargentin, 1761-1762: 212-213), and made the following short remarks and cautious conclusion:

It is worth noting that the limb of Venus, which then had emerged, was conspicuous even outside the Sun, as a kind of weak light occurred [over Venus' limb] and lasted during the entire emersion. Whether such a sight of the edge of Venus is due to the bending of the rays of the Sun, or to refraction in the atmosphere of Venus – is for others to decide. (my English translation).

Wargentin's drawing (Figure 4) presents the aforementioned phenomenon in a somewhat improbable way (is the lower part of Venus dark or is it illuminated?), and with Venus' size completely out of proportion to that of the Sun. Another, earlier, drawing by Wargentin (see Strömer et al., 1761) is presented as *fig.13* in our Figure

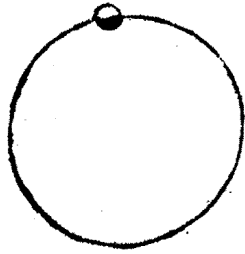


Figure 4: Drawing by P.W. Wargentin (after Wargentin, 1761-1762: 213); see, also, his *fig. 13* in Figure 5 below.

5 (see the discussion below) and better illustrates what he actually saw.

From the observatory founded by Anders Celsius in Uppsala, Sweden, astronomer Professor Mårten Strömer (1707–1770) observed the 1761 transit of Venus with a 20-ft non-achromatic refractor. Strömer was assisted by Torben Bergman (see above) and Frederick Mallet (1728–1797), the Professor of Mathematics at the University, who used an 18-in long reflector. Both Strömer and Mallet also saw the arc at ingress and egress and included corresponding drawings in their initial report (see Figure 5 below). This report (Strömer, et al., 1761) is not dated but could be placed in the third quarter of 1761 at the earliest.

Mallet described *fig. 6* in Figure 5 as follows:

Once Venus was three-quarters of the way onto the Sun, it was noted by all observers that a weak glow or streak surrounded the remaining fourth, to show Venus entirely round (Fig. 6). H. Mallet also saw through the telescope that the Sun extended small fine horns to surround Venus; to begin with he believed these to stem from a small defect in the telescope, as always tends to happen with objects that are close to the horizon or otherwise are covered by thin clouds or fog, but when Venus moved further onto the Sun, the deviations from the Sun's circular figure, which the horns formed, were seen even more clearly. (Strömer et al., 1761: 146; English translation by Dr Andreas Jansson).

Meanwhile, here is Strömer's description of *fig. 10*:

... at 9, 28,0 Venus' edge seemed to him to touch that of the Sun: and when this moment

had been written down, and the Sun's edge was again observed at 9, 28,7 it was more open than he had expected (Fig. 10). The Sun's horns *a, b* seemed quite blunt, and one should judge from this that Venus was still entirely inside the Sun's disc – although the Sun's edge was dark or covered. The outer tangent of the Sun's and Venus' edges became uncertain by a ... shaking of the tube, causing the lens to move, so that it is uncertain if the correct focus was found. Venus appeared then no longer connected to the Sun at 9. 46m.15 s. These observations were comparable to those of the others present. (Strömer et al., 1761: 150; English translation by Dr Andreas Jansson).

Subsequently, Strömer et al. (1761: 151) reported that:

While Venus was exiting the Sun, at first the exiting portion seemed surrounded by a narrow and faint glow: then it did not extend further than a portion of Venus, as the exiting portion increased. Different observers saw the extent of the glow to be of different magnitudes. Before Venus had half exited, which according to H. Strömer appeared to happen at 9. 35 m. 11 sec, the Sun's horns appeared to extend and surround Venus in a similar manner as during the entry: the tips of the Sun's horns always seemed too blunt against Venus' small disc, and when she was about to detach from the Sun, H. Mallet thought that she stuck to the Sun too much against her round shape, but at the end he became aware that Venus' round edge changed into an angular figure (Fig. 12), which to begin with was blunt, but then became pointed. (English translation by Dr Andreas Jansson).

Although Mallet and Strömer did not initially draw the conclusion that the observed phenomena had an atmospheric origin, later Mallet (1766) supported Wargentin's version of such an explanation. Their drawings 6–12 in Figure 5 feature correct proportions, but are somewhat schematic, as shown by the uniform thickness of the arc, and the sharp joining of the arc to the Sun's disc (as also seen in Bergman's drawings, above).

The prominent French astronomer Abbe Jean Chappe d'Auteroche (1722–1769) observed the transit from Tobolsk in the Asian part of Russia

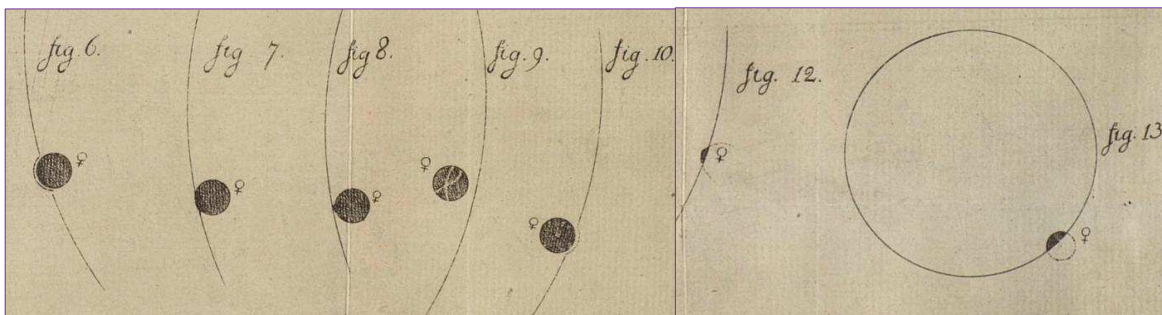


Figure 5: The 1761 transit observations from Uppsala, Sweden (after Strömer, et al, 1761: 167).

with a 19-ft non-achromatic refractor. His results were delivered orally to the St. Petersburg Academy of Sciences on 11 January 1762 and published by the Academy shortly thereafter (see Chappe d'Aueroche, 1762). A copy of his report was published in 1763 by the French Royal Academy of Sciences (Chappe d'Aueroche, 1763), and both papers have essentially the same set of illustrations (shown here in Figure 6). During ingress (*Fig. 1* in this Figure) Chappe d'Aueroche (1762: 14) reported:

...I could see the part of the disc of Venus that had not yet entered [the Sun], and a small ring-shaped atmosphere around this disc ... (my English translation).

Similarly, at egress (*Fig. 2* in Figure 6)

... one can see that part of the disc of Venus which is already out, and a crescent-shaped ring, of which the convex part is turned towards the inferior edge of Venus. (Chappe, d'Aueroche 1762: 15; my English translation).

In Figure 6, Chappe d'Aueroche's *Figs. 3* and *4* show the illuminated crescent structure of Venus at various moments during the transit.

As we have seen, Chappe d'Aueroche claimed to have seen at ingress and egress "... a small ring-shaped atmosphere ..." on that part of the disc of Venus that was off the Sun. This luminous arc was described as a very broad crescent roughly a quarter of Venus' radius, but it changed its dimensions and orientation as Venus traversed the Sun. This phenomenon does not match any other observations made during the 1761 transit, or later transits for that matter. In his 1763 report Chappe d'Aueroche attempts to explain the crescent as being part of Venus side-illuminated by the Sun (which stemmed from the argument that the Sun's angular size was significantly larger than that of Venus). However, it is easy to understand, from purely geometrical considerations, that such an illumination cannot be projected on the part of Venus which was outside the Sun's disc. Sharonov (1960: 36) also argues that even while the planet was on the Sun, the zone that would be side-illuminated should seem much thinner and darker than shown in Chappe d'Aueroche's drawings.

Given these improbable observations and explanations, one must question the relatively high degree of credibility attributed to Chappe d'Aueroche's observations in several reviews (e.g., see Meadows, 1966; Link, 1959; 1969; Pasachoff and Sheehan, 2012a). We should note that Chappe d'Aueroche's contemporaries viewed his observations quite differently. For example, a prominent member of the French Royal Academy of Sciences, Baron Frederick Melchior de Grimm (1723–1807), wrote to the encyclopedist Denis Diderot about Chappe d'Au-

teroche's results:

... the work has but just appeared, and it is already so decried, that no person of sense will place the least confidence in it. The Academy of Sciences itself hesitates whether it ought in any way to rely upon the astronomical observations which the Abbe has sent from Siberia. Many of our Academicians say that there is good reason to doubt both the accuracy of the observations, and the truth of the report. They are very much led to suspect, on comparing this report with the observations of other astronomers upon different parts of the globe, that the Abbe did not in fact see the transit at all, that the Sun was veiled by clouds during the whole time that it took place, but that not being willing to lose entirely the fruits of his journey, he sat himself down in his room

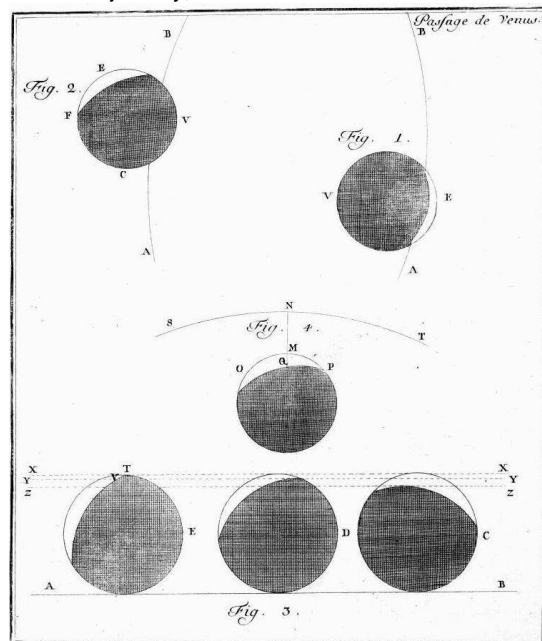


Figure 6: Drawings by Abbe Chappe d'Aueroche depicting the ingress and the egress during the 1761 transit of Venus (after Chappe d'Aueroche, 1762: 23).

to calculate the probable beginning, progress, and end of the event, and presented these calculations as the result of his observations. This suspicion is probably based upon something that may have stupidly or ignorantly been said by one or other among the companions of our astronomical adventurer. They may perhaps have said, that the Sun did not appear at all that day at Tobolsk; the Abbe himself speaks of his anxiety at this most important moment of his journey, upon seeing the clouds which covered the horizon at sunrise, but then he dwells no less upon his travels when the Sun had dispersed these clouds; he speaks of all this, however, in the perfect tone of a libertine scholar. (Grimm et al., 1850: 378; my English translation).

We do not know all the arguments used against Chappe d'Aueroche then, but one can suppose that such suspicion could partly be due to his

changing the contact times from publication to publication (for example, there is a 7-second difference between Chappe d'Aueroche (1761-1762) and Chappe d'Aueroche (1768)).

Chappe d'Aueroche's skills and experience as a practising astronomer also were questioned in the report of a local Tobolsk authority on how unprofessionally Chappe d'Aueroche handled his 19-ft telescope (see d'Encausse, 2003: 327-329).

Several other observers of the 1761 transit of Venus reported seeing the arc, but they did not provide any drawings. The German Georg Christoph Silberschlag (1731–1790) observed the transit from the 'Kloster Berge' Monastery and published a short emotional note one week later in the popular weekly newspaper *Magdeburgische Privileg Zeitung*:

It has to be mentioned that when Venus was touching the Sun's inner border, the solar border expanded into a region parallel to Venus' circumference. Experts will ascribe this phenomenon definitively to the action of Venus' atmosphere, in which strong refraction of light must take place. Interesting circumstance! The existence of Venus' atmosphere, which could be claimed to exist only by analogy thus far, is now confirmed by the observation. Venus is certainly a planetary body just like the Earth, especially since high mountains were already observed by Cassini. We add: one could object to the claim that Venus has an atmosphere by pointing out that every solid body will bend light that passes in close proximity, even in a vacuum. However, the refraction was too strong. And as one could see very clearly the transit of Venus over the Sun from the 5th to almost the 7th hour one could also recognize a fringe around the very rotund Venus, which probably cannot be explained by any other reason than the existence of an atmosphere. (Silberschlag, 1761; English translation by Dr Wolfram Fischer).

Eight years later, this report appeared in essentially the same form in a scientific publication (see Kordenbusch, 1769: 55-56). One has to note that besides the arc at egress, which is generally conceded to be an atmosphere-induced phenomenon (*P*), for several hours Silberschlag also observed a ring around Venus as it transited the Sun's disc (*P**V*), a phenomenon that was not associated with Venus' atmosphere (see the discussion below).

Reverend William Hirst (d. 1774), the Chaplain on one of His Majesty's (i.e., George III's) Ships in the East Indies used a 2-ft reflector to observe the 1761 transit from Madras, India, on behalf of the Royal Society of London (Kapoor, 2013). After the event Hirst wrote to the President of the Society announcing that during the transit he had seen an atmosphere around Venus:

The morning proved favourable to the utmost of their wishes, which the more increased their impatience. At length, as Mr Hirst was steadfastly looking at the under limb of the Sun, towards the south, where he expected the planet would enter, he plainly perceived a kind of penumbra, or dusky shade ... Mr. Hirst is apprehensive, that to be able to discern an atmosphere about a planet at so great distance as Venus, may be regarded as chimerical; yet affirms, that such nebulousity was seen by them, without presuming to assign the cause. They lost sight of this phenomenon as the planet entered the disk, nor could Mr. Hirst perceive it after the egress. (Hirst, 1761: 397-398).

By the time the 1769 transit occurred Hirst was back in England and he carried out successful observations, but what is interesting is that in his report he also refers to his 1761 observation of an atmosphere around Venus:

... when I took the observation of the transit of Venus at Madras, in the year 1761, I saw a kind of penumbra or dusky shade, which preceded the first external contact two or three seconds of time, and was so remarkable, that I was thereby assured the contact was approaching, which happened accordingly ... (Hirst, 1769: 231; his italics).

The distinguished Russian scientist and University of St. Petersburg Professor, Stepan Rumovsky (1734–1812) observed the transit from Selenginsk (east of Lake Baikal) with a 15-ft non-achromatic refractor and briefly commented (in just one sentence) that at egress "... the leading edge of Venus seemed to be surrounded by a circle of light." (Rumovsky, 1762; my English translation).

There is a short note by Lomonosov (in Vavilov and Kravets, 1950-1983(X): 577) that another noted Russian astronomer, Academician Nikita Ivanovich Popov (1720–1782), also saw Venus' atmosphere when he observed the transit from Irkutsk, but no details were found in Popov's recently-discovered logbooks and unpublished reports (see Kuznetsova, 2009).

The well-known French astronomer, Pierre Charles Le Monnier (1715–1799), observed the transit from the Chateau de Saint-Hubert at Perray-in-Yvelines (near Paris) in the presence of the King. He used an 18-ft non-achromatic refractor. In his report on the transit, Le Monnier (1763) mentions that:

... the Sun was always perfectly clear, and often too bright as the glass has been very lightly smoked, and there was no glimpse of an atmosphere around Venus, not even during the final moments of the transit, when the Sun was most fiery ... [At egress] however, I saw for a minute or two the entire disk of Venus, although it was already partly out of the Sun, but I was not certain as to the duration of this appearance ... (my English translation).

It is notable that Le Monnier (a) expected that the atmosphere of Venus would appear while the planet was on the Sun, yet he did not see any aureole or penumbra; and (b) was the only astronomer known, besides Lomonosov, who specifically mentioned using a lightly-smoked glass (i.e. a weak solar filter).

3.2 Observations of an 'Atmosphere' During the External Contacts (*PII*)

Currently, there is still no complete agreement on whether the disturbance of the solar limb during the external contacts is an indication of Venus' atmosphere. Given how short the moment is, it is not surprising that very few observers reported it.

The Russian scientist Joseph Adam Braun (1712–1768) from the St. Petersburg Imperial Academy of Sciences observed the blurriness with an 8-ft non-achromatic refractor but doubted its relation to Venus' atmosphere, perhaps in response to the claims by his fellow St. Petersburg Academician, Lomonosov:

As far as the beginning is concerned, what I particularly noticed as the disc of Venus began to lose its rotundity, when Venus began to enter [the Sun], it did not appear as in progress, perfectly black and round, but was rather dark, irregular, and rough, perhaps the cause was the vapors in the atmosphere, yet I hesitate to attribute this irregularity to the atmosphere of Venus. (Hell, 1762: 92-94; my English translation).

3.3 A Circular 'Atmospheric' Ring Around Venus While it was on the Sun (*PIV*)

The most popular category of the 1761 reports in which the word "atmosphere" occurs—and more than a dozen by my count—related to observations of 'rings' around Venus while it was fully on the disc of the Sun. The large number of such reports is presumably related to widespread expectations of how the planet's atmosphere would manifest itself (see the discussion on Le Monnier above), and the fact that Venus spent many hours transiting the Sun (contrary to the relatively short ingress and egress periods of less than 20 minutes), and to the fact that in the eighteenth and nineteenth centuries such aureoles were observed during transits of Mercury (which has no atmosphere), as Sharonov (1960) has noted.

The phenomenon is not predicated by current models of refraction in Venus' atmosphere (García-Muñoz and Mills, 2012), and should most probably be attributed to imperfections of the optical instruments rather than being related to atmospheric effects (see Meadows, 1966). The illusive nature of the *PIV* phenomenon can be concluded from the great variety of observation-

al results: the aureole looked like a bright ring to some (e.g. Dunn, 1761-1762); a dark penumbra to others (e.g. Ferner, 1761-1762); a pale red ring (e.g. Maraldi, 1763); a very broad cloud-like aureole up to one-quarter of Venus' diameter (e.g. Rohl, 1762); or a thin aureole only 1/400 of the planet's diameter (e.g. Dunn, 1761-1762). Among others who noticed an 'atmospheric ring' around Venus during the transit were Desmaires and de Mairan (see d'Auteroche, 1763: 365), Fouchy (1763), Hellant (1761) and Planman (1768).

The Professor of Astronomy at Greifswald University in Germany, Lambert Heinrich Röhl (1724–1790), observed the transit from near Greifswald with a 16.5-ft non-achromatic refractor and noted the full spectrum of luminous phenomena: a penumbra-type ring around Venus while the planet was on the solar disc (*PIV*); the formation of a 'hump' on the solar limb at 3rd contact (*PI*); and a disturbance of the solar limb at the end of the egress (*PII*) (Röhl, 1762). Some of these are shown in Figure 7, below, where *Fig. II* explains the phenomena at external contact; and *Fig. III* shows the formation of the 'hump' at 3rd contact. *Fig. IV* illustrates the effects seen at egress. Röhl concluded:

But what immediately emerged from the observations was an amazing depth of knowledge about the atmosphere of Venus, which is one quarter the diameter of the planet and therefore is significantly bigger in comparison to the Earth's atmosphere of several miles; also a slight refraction of rays reveals the atmosphere of Venus. Horizontal refraction on Venus exceeds ten seconds. All this seems to agree very well with nature. Of course, one may conclude by analogy, that the action of the atmosphere exposed to the nearby solar rays is greater and that refraction of light diminishes with ascending height. (Röhl, 1762: 12; my English translation).

The physics of the refraction leading to the observed effects is shown in good detail in Figure 7, but the abnormal thickness of the presumed atmosphere of about one quarter the diameter of Venus most probably indicates serious optical imperfections in the telescope. In a subsequent publication Röhl (1768) discusses the 1761 results in more detail, and he reviews the many other aureole observations that he was aware of.

3.4 Observations of the 'Atmosphere' During the 1769 Transit of Venus

The last transit of Venus in the eighteenth century took place eight years later, on 3 June 1769. The 1761 indications of a Venusian atmosphere, although not widespread, did not go unnoticed, and several reviews on the subject were published (e.g. see Chappe d'Auteroche,

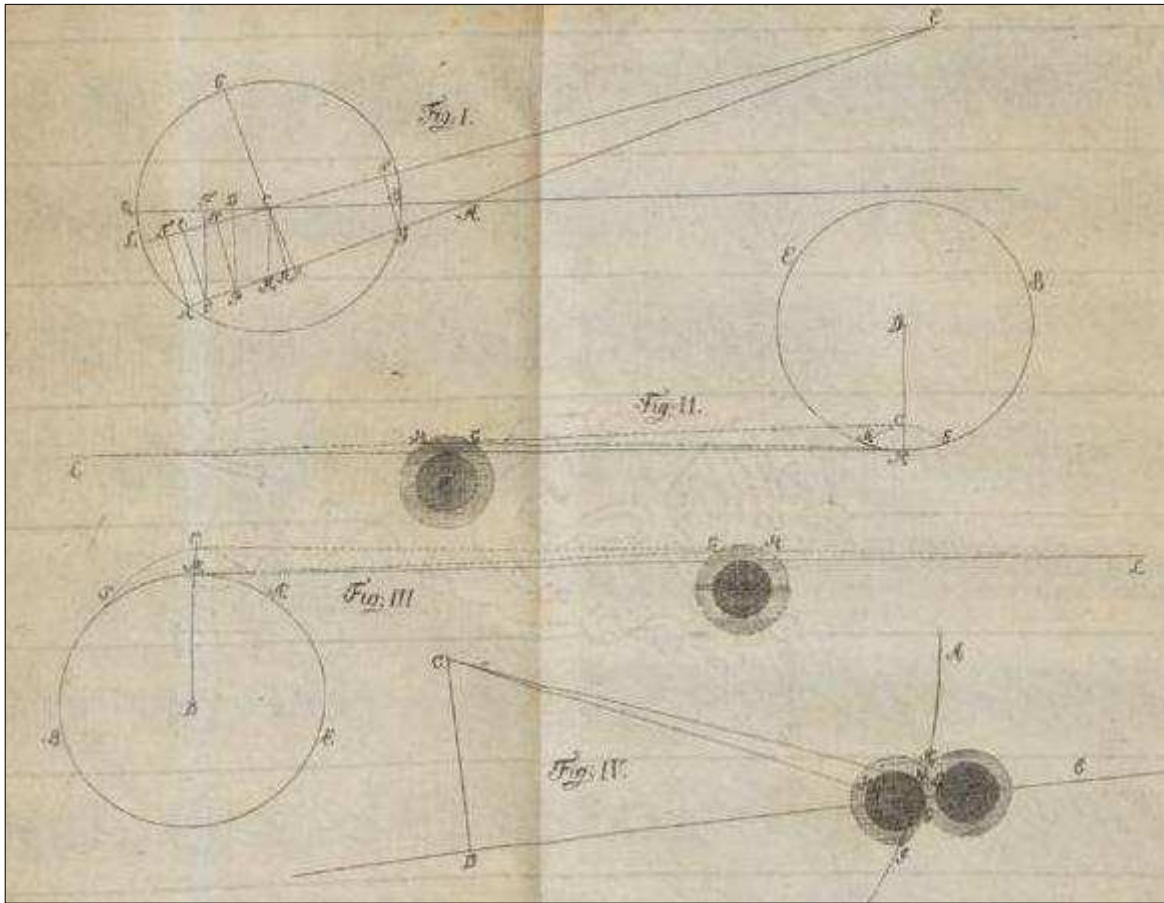


Figure 7: Evidence of an atmosphere around Venus, as observed by Lambert Heinrich Röhl (after Röhl, 1762: 13).

1763; Röhl, 1768). The phenomenon was deemed worthy of further exploration, and was discussed by Rumovsky (1771: 41-56) and Maskelyne (1768) in preparation for the 1769 transit. Stepan Rumovsky's instructions written and accepted in 1767-1768 essentially summarized Lomonosov's experience with observing the atmosphere and called for observers to adopt relaxed positions for the body and to make observations with well-rested eyes. British Astronomer Royal Nevil Maskelyne (1732–1811) paid serious attention to the procedures for the fabrication of smoked-glass filters for use in 1769. As a result, many more observations of phenomena *PI-PIV* were reported after the transit. Below only a few of the results are presented, which will be relevant to the discussion in Section 5.

The renowned American self-taught astronomer, David Rittenhouse (1732–1796), observed the transit at Norriton, near Philadelphia, with a 36-ft focal length 3-inch aperture non-achromatic refractor, and saw outward-looking pyramids of light around the planet after it advanced about one third of its diameter onto the Sun (see Figure 8). This unusual structure broadened and spread completely around the circumference of Venus that was off the Sun after the middle of

the ingress and got brighter as the second (internal) contact approached. Rittenhouse provided the following detailed description:

When the Planet had advanced about one third of its diameter on the Sun, as I was steadily viewing its progress, my sight was suddenly attracted by a beam of light, which broke through on that side of Venus yet off the Sun. Its figure was that of a broad-based pyramid; situated at about 40 or 45 degrees on the limb of Venus, from a line passing through her center and the Sun's, and to the left hand of that line as seen through my telescope, which inverted. See TAB.XV. fig.1 - About the same time, the Sun's light began to spread round Venus on each side, from the points where their limbs intersected each other, as is likewise represented in fig.1. As Venus advanced, the point of the pyramid still grew lower, and its circular base wider, until it met the light which crept round from the points of intersection of the two limbs; so that when half the Planet appeared on the Sun, the other half was entirely surrounded by a semicircular light, best defined on the side next to the body of Venus, which constantly grew brighter, till the time of the internal contact. See fig.2. Imagination cannot form any thing more beautifully serene and quiet, than was the air during the whole time; nor did I ever see the

Sun's limb more perfectly defined, or more free from any tremulous motion; to which his great altitude undoubtedly contributed much. When the internal contact (as it is called) drew nigh foresaw that it would be difficult to fix the time with any certainty, on account of great breadth and brightness of the light which surrounded that part of Venus, yet off the Sun. After some consideration, I resolved to judge as well as I could of the co-incidence of the limbs; and accordingly gave the signal for the internal contact at 2h28'45" by the clock, and immediately began to count seconds, which any one, accustomed to it, may do, for a minute or two, very near the truth. In this manner, I counted no less than 1'32" before the effects of the atmosphere of Venus on the Sun's limb wholly disappeared, leaving that part of the limb as well defined as the rest. (Smith et al., 1769: 310-312).

Rittenhouse did not offer any explanation for these observations. The outward-looking ray-like fractured-light aureole (a bunch of wide rays of light) as Rittenhouse described is not how refracted light is supposed to be shaped, and essentially has not been seen in an identical form by any other observer over the past six transits. Still there might be grounds for some scholars to qualify Rittenhouse's observations as the *PI* phenomenon accompanied by some optical illusions (e.g. see Pasachoff and Sheehan, 2012a). Rittenhouse's drawings are of high quality and in correct proportion, so the height of the 'light pyramids' can be estimated to be 4"-11".

One of Rittenhouse's collaborator was John Lukens (1720?–1789), the Surveyor-General of Pennsylvania and Delaware, and he noticed "... a large tremulous shadow ..." at the point of the 1st (external) contact (phenomenon *PII*), and very briefly described "...a border of light encompassing the part of her (Venus) that was yet off the Sun ..." (phenomenon *PI*). Another collaborator, Dr William Smith (1727–1803) the Provost of the College (later University) of Pennsylvania, also reported seeing phenomenon *PII* at the external contact, and *PIII* similar to that observed by Lomonosov prior to internal contact:

... as to the internal contact, the thread of light, coming round from both sides of the Sun's limb, did not close instantaneously, but with an uncertainty of several seconds, the points of the threads darting into each other, and parting again, in a quivering manner, several times before they finally adhered. (Smith et al., 1769: 315).

He also analyzed a tremulous motion at the point of the external contact (*PII*) as follows:

... as for the first disturbance made on the Sun's limb, it may be worth considering, whether it was really from interposition of the limb of Venus or of her atmosphere? The former, one

could not easily imagine it to be, unless her limb and body were more uneven than they appeared to be seen on the Sun. An atmosphere it might more probably seem to be, not only from the faintness of the colour, but the undulatory motion, which might arise from the growing density of the atmosphere, as it pushes forward on the Sun, varying the refraction of the rays. If such an atmosphere be allowed, then it probably gives the same tremulous motion, at the internal contact, to the thread of light creeping round Venus; and prevents its closing quietly till the atmosphere (or at least its densest part) be wholly on the Sun; and consequently the true coincidence of the limbs be past. For though the atmosphere of Venus can not be seen on the Sun, yet part which is surrounding, or just entering on the Sun's limb, having, as it were, a darker ground behind it, may be visible. But these are only little conjectures submitted to others; though if they have any foundation, it would make some difference in the time estimated between the contacts. (Smith et al., 1769: 316-317).

The Royal Observatory's Charles Green (1735–1771) and career Naval officer Lieutenant James Cook (1728–1779) were the two official astronomers on the expedition organised

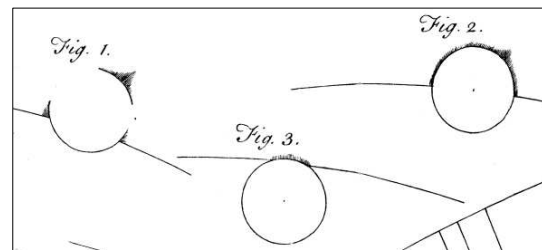


Figure 8: David Rittenhouse's 1769 drawings of the ingress (after Smith et al., 1769: plate XV 311).

by the Royal Society (of London) to observe the 1769 transit from "King George's Island in the South Sea" (Tahiti), but they were assisted by a number of other officers and supernumeraries from *H.M.S. Endeavour* located at three different observing sites on or just off the coasts of Tahiti and Morea (for details see Orchiston, 2005). Green later died at sea on the passage home from Batavia (now Jakarta) and all the astronomical observations apparently were prepared for publication by Cook with assistance from Nevil Maskelyne (the Astronomer Royal). Even though eleven different individuals successfully observed the transit, for some unexplained reason observations made by only three of them (Cook, Green and one of Joseph Banks' retinue, the botanist Daniel Solander) were included in the paper that was published in the *Philosophical Transactions of the Royal Society*. In this paper Green and Cook (1771) reported seeing a pale waterish penumbra of a thickness about 1/8th of Venus' semidiameter around the planet while it was on the Sun (*PIV*), and possibly phenomenon *PII* (disturbance of the solar limb

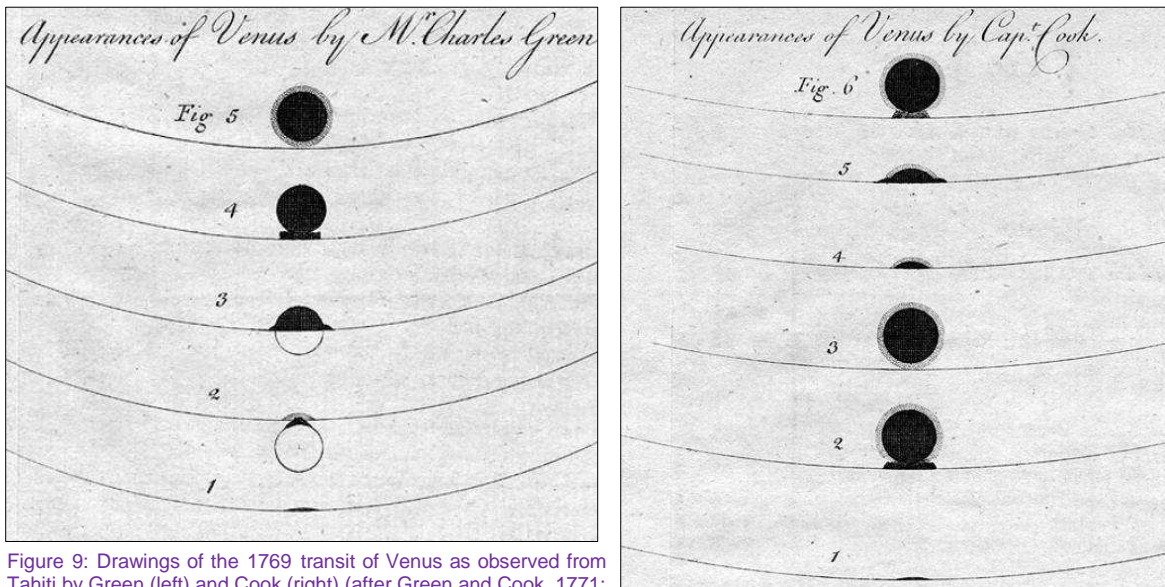


Figure 9: Drawings of the 1769 transit of Venus as observed from Tahiti by Green (left) and Cook (right) (after Green and Cook, 1771: 410).

at external contact) during the ingress—see Green's Figure 4 in our Figure 9 above.

Maskelyne (1769: 357-359, 363) also observed the transit from the Royal Observatory at Greenwich, and he clearly saw the arc (*PI*) but did not see the aureole (*PIV*):

It had been thought by some, that Venus' circumference might probably be seen in part at least, before she entered at all upon the Sun, by means of the illumination of her atmosphere by the Sun; I therefore looked diligently for such an appearance, but could see no such thing.

I was also attentive to see if any penumbra or dusky shade preceded Venus' first impression on the Sun at external contact, such a phenomenon having been observed by the Rev. Mr. Hirst, F.R.S. at the former transit of Venus, in 1761, which he observed with much care and diligence at Madras, in East-Indies; but could not discern the least appearance of that kind ... When Venus was a little more than half immersed into the Sun's disc, I saw her whole circumference completed, by means of a vivid, but narrow and ill-defined border of light, which illuminated that part of her circumference which was off the Sun, and would otherwise have been invisible. This I might probably, have seen sooner, if I had attended to it ...

An ingenious gentleman of my acquaintance having desired me to examine if there was any protuberance of the Sun's circumference about the point of the internal contact, as he supposed such an appearance ought to arise from the refraction of the Sun's rays through Venus' atmosphere, if she had one; I carefully looked out for such a circumstance, but could see no such thing; neither could I see any ring of light around Venus, a little after she was got wholly within the Sun: but, I confess, I did not re-examine this latter point after-

wards, when she was further advanced upon the Sun, at which time other persons at the observatory saw such an appearance ... How far the ring of light, which I saw round that part of Venus' circumference which was off the Sun, during the immersion, may deserve to be considered as an indication of an atmosphere about Venus, I shall not at present inquire; but I think it very probable, that the protuberance, which disturbed Venus' circular figure at the internal contact, was owing to the enlargement of the diameter of the Sun, and the contraction of that of Venus, produced by the irregular refraction of the rays of light through our atmosphere, and the consequent undulation of the limbs of the two planets.

Notably, Maskelyne is quite cautious in attributing the arc to Venus' atmosphere, while he implied that the black protuberance at and after the internal contact (phenomenon *PV*)—now referred to as the 'black drop effect' (see Schaefer, 2001)—is due to turbulence in the Earth's atmosphere.

Maskelyne had invited a group of experienced observers to view the transit with him, and they produced a wide variety of descriptions, with some seeing and some not seeing the *PI*, *PII* and *PIV* phenomena (Meadows, 1966). One of them, the Reverend William Hirst (who observed the 1761 transit from Madras in India) also observed "... a violent coruscation, ebullition, or agitation of the upper edge of the Sun ..." five or six seconds before 1st contact (see Figure 10), very much like Lomonosov's phenomenon *PII*. What made Hirst (1769) believe that the effect was not an optical deception, but perhaps was due to Venus' atmosphere, was that the remaining parts of the Sun's limb, at and beyond points *a* and *b*, remained perfectly quiescent.

3.5 Summary of the Observations of the Atmospheric Effects in 1761

Four different types of aureole phenomena were observed during the 1761 transit. More than a dozen observers reported seeing either a bright or pale penumbra around the disc of Venus while the planet was on the Sun's disc (*PIV*), a phenomenon that cannot be attributed to the atmosphere. Very few saw light radiances at the very time of internal contact, (*PIII*), a phenomenon that could in principle be caused by Venus' atmosphere, but much more convincingly was attributed to telescope imperfections or optical illusions. Similarly, the appearance of tremulous motion on the edge of the Sun prior to the point of external contact (phenomenon *PII*) could hardly be accepted as an indication of the planet's atmosphere with any high degree of certainty. Contrary to phenomena *PIV*, *PIII* and *PII*, the observation of the arc of light outlining the part of Venus' disc off the Sun during ingress or egress (*PI*) assumes "... seeing an arc of light at the place where there should be nothing (black background) if the atmosphere is absent ...", and, therefore, can be considered as a true manifestation of Venus' atmosphere, as it is now understood and modeled from the first principles of physics (see Garcia-Muñoz and Mills, 2012). Slight variations in the observed features of the phenomenon (full arc or partial arc, 'whiskers', different degrees of brightness) could be attributed to differences in the instruments and methods used, namely the type of telescope, the aperture of the objective lenses, the attenuation of the solar filters, etc. Finally, the 'black drop effect' (phenomenon *PV*) was reported by many eighteenth century observers and was already understood to be an artificial, purely optical, nuisance that bore no relation to Venus' atmosphere.

Table 1 summarizes all reports known to the author of sightings of the arc (phenomenon *PI*) during the 1761 transit, and three 1769 observations relevant to the discussion in Section 5 below. The table contains information about the instruments and methods used (telescope types: 'A' = achromatic refractor, 'N' = non-achromatic refractor, 'R' = reflector, with the length in feet; the aperture of the objective and the type of solar filter; thickness of the observed luminous arc off the Sun's disc where illustrations are provided, which serves as an indicator of the quality of the instrument and, of course, of the seeing at the time of the observation); date of publication (the first communication which in most cases reflects the time of the report's submission and the time of publication of the original scientific report); quality of the report and of the atmosphere question (length of the report and length of the atmosphere discussion, number of illustrations, depicted ratio of Venus-to-Sun diameters as an indication of the quality of illu-

strations), depth of the physics reasoning for a presumed atmosphere of Venus (whether refraction in Venus' atmosphere is mentioned, and whether a detailed explanation of refraction-induced phenomena has been offered).

Let us see how different observers fare using these criteria.

Quality of the Instruments and the Methods: seemingly all the observers except Green had instruments sufficient for the arc observation. Nevertheless, assuming approximately similar objective lens diameters (~2"–3"), the equivalent chromatic and spherical aberrations occur in achromatic refractors, which are about 16 times shorter than non-achromatic refractors (Maksutov, 1979). In 1761, the achromats were a relative novelty: according to Newcomb (1891), out of 97 reports of the 1761 transit, a majority (47) used non-achromats, 25 employed reflectors, and only 3 had achromatic refracting telescopes which had recently been made available by Dollond (the remaining 22 optical systems were not

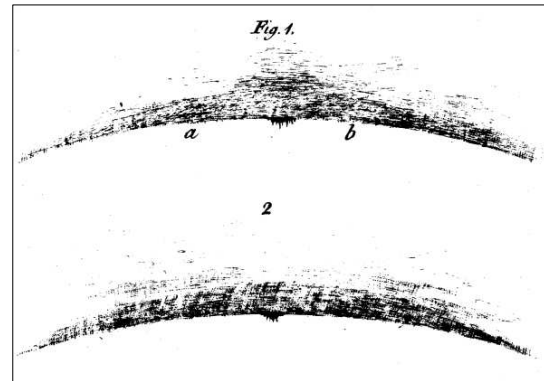


Figure 10: Phenomena recorded by William Hirst preceding the 1st (external) contact during the 1769 transit of Venus (after Hirst, 1769: 229).

identified). Therefore, one might expect that Lomonosov's 4½-ft long achromat was capable of outperforming all the listed non-achromats of between 12 and 36-ft focal length. The fact that the thickness of the arc observed by Lomonosov (about 3.7") is the smallest among the various reports supports this conclusion. Also, only Lomonosov and Le Monnier specifically mentioned using weak solar filters—the method critically helpful to assure observation of the arc, as shown in the 2012 replication experiment (Koukarine, et al., 2012). So, overall, one can consider Lomonosov to have had an advantage in the quality of his instruments and methods.

Time of Publication: although we list the dates of the first recorded communications on the subject, they probably are not that relevant due to the diversity of media used (private communications, reports, newspaper notes). Seemingly all the listed observers immediately appreciated any unusual effects they observed and communicated them one way or another. (As an exaggeration,

Table I: Summary of 1761 and 1769 transit of Venus observations reporting a luminous arc off the Sun at ingress and/or egress.

	1761										1769 (some)		
	Lomonosov	Bergman	Wargentin	Chappe D'Aueroche	Mallet	Strömer	Silberschlag	Hirst	Rumovsky	Le Monnier	Green	Rittenhouse	Maskelyne
Telescope	A, 4½	N, 21	N, 19	N, 19	R, 1½	N, 20	N,12/ 24	R, 2	N, 15	N, 18	R, 2	N, 36	R, 2
Aperture	2.1" - 2¾" (?)	No data	1.75"	2"	No data	No data	No data	No data	No data	No data	No data	3"	No data
Filter	Weakly smoked glass	Green & weak red glass	Smok- ed glass	No data	Green glass	Red glass	No data	No data	No data	Lightly smoked glass	No data	Deeply smoked glass	Smok- ed glass?
Arc thick- ness	~3.7"	~5.7"	--	off/on Venus 5-7.5"	4-5"	5-6"	--	--	--	--	no arc, 8" penum- bra	Pyra- mid 4"-11"	--
1 st commun- ication	June 07	Aug. 28	June 09	Aug. 24	--	--	June 13	July 01	Apr. 26, 1762	June 10	Apr 13, 1770?	July 18	--
1 st scientific. publication	July 15	Nov. 19	Nov. 12	Jan. 11 1762	Q3 1761	Q3 1761	1769	Apr. 22 1762	July 08, 1762	1763	Nov. 21 1771	1769	June 15 1769
Report Length (pp.)	17	5	6	22	8	8	2	3	28.	5	25.	14	12
Information on the arc	3 pp.	½ p.	4 lines	½ p.	9 lines	12 lines	½ p.	8 lines	11 lines	9 lines	1 p.	~1 p.	2 pp.
Illustrations	8	6	1	4	1	1	None	None	None	None	5	4	None
Venus/Sun diameter	1:32	1:10	1:9	1:7	1:30	1:30	--	--	--	--	1:31	1:32	--
Refraction explained	Yes	No	No	No	No	No	No	No	No	No	No	No	No
Reconstruc- tion	2012	--	--	--	--	--	--	--	--	--	--	--	--

one could claim that the first who saw the arc was Stepan Rumovsky as his station was the furthest eastward). Following the generally-accepted rules regarding priority in science, which consider only the time of the publication of the first scientific report, it seems clear that Lomonosov was the first to formally publish a paper with observational data of the aureole interpreted as evidence for Venus' atmosphere. This should be sufficient to establish his priority of discovery.

Comprehensiveness and the Quality of the Scientific Report. Although the total length of Lomonosov's 1761 report is second only to Rumovsky's (17 vs 28 pages), it is much more important to consider how detailed is the discussion of Venus' atmosphere, as that alone shows appreciation of the importance of the observation by the observer. Seemingly, the arc was considered as a nuisance by Hirst, Le Monnier, Rumovsky and Wargentin, as they only allocated several lines of text to a description of the phenomenon. Bergman, Chappe d'Aueroche, and Silberschlag were a little more expansive as they not only dedicated about half a page to the effect, but the first two also illustrated their observations with one or more drawings. Still, in that regard, Lomonosov's report is an absolute leader: not only did he elaborate at length on the effects due to Venus' atmosphere, but he also

provided eight drawings to better explain his observations and reasoning. Moreover, his drawings are of amazing accuracy as indicated by the correct ratio of the diameters of Venus to the Sun, so one can use them with conviction for scientific data processing (as Sharonov did in 1952). The drawings by Bergman, d'Aueroche and Wargentin are given mostly for illustrative purposes, and show the observed phenomena out of proportion. Note that the drawings of the 1769 transit by Rittenhouse and Green are of high quality and trustworthy, too, and the 1769 report by Maskelyne contains an equally-detailed description of the phenomena. One can presume that such an attention to detail in 1769 was due to awareness by the astronomers of the potential appearance of Venus' atmosphere, an advantage which neither Lomonosov nor any of the other 1761 observers enjoyed.

Depth of Physics Reasoning for the Atmosphere of Venus: Among the 1761 observers of the arc, only Lomonosov, Silberschlag and Wargentin concluded that the arc is caused by refraction of sunlight through the atmosphere of Venus, the last-mentioned with some caution, and the first two astronomers in a much more assured way. Lomonosov's advantage in this category is unquestioned, as he is the only one to give a correct physical explanation of refract-

tion, with illustrations and detail matching that shown in modern optics textbooks.

Replication of the Observation: Finally, it has to be taken into account that only Lomonosov's observation was successfully replicated during the transit of 2012, and a thin arc of light on that part of Venus off the Sun's disc during the ingress (*PI*) was successfully detected with original eighteenth-century Dollond achromatic refractors similar to that deployed by Lomonosov, and with his experimental techniques carefully emulated (e.g., lightly-smoked glass filters, and periodic rest for the eyes to maintain sensitivity; see Koukarine et al., 2012).

Therefore, the detailed analysis of all optical effects observed during the 1761 transit of Venus shows that only 9 astronomers (with two possible additional ones, Chappe d'Auteroche and Popov, still classed as doubtful) actually saw the aureole caused by refraction of sunlight in the atmosphere of Venus during ingress or egress. Of all of them, Lomonosov should be credited with priority for the discovery because he:

- (1) expeditiously and formally published his scientific results;
- (2) was one of the few to understand the effect and was the only one to offer an in-depth physics explanation of the aureole due to refraction in the atmosphere of Venus; and
- (3) displayed comprehensiveness and quality in his scientific reporting, for his description of critically-important methods (e.g. the use of a very weak solar filter with an achromatic telescope) allowed replication of his discovery more than two and a half centuries later.

Note that the first two arguments listed above were laid out long ago by Perevozshikov (1865), Sharonov (1952b; 1960) and Chenakal and Sharonov (1955).

4 FURTHER DEVELOPMENTS DURING THE EIGHTEENTH, NINETEENTH AND TWENTIETH CENTURIES

The present version of the situation was far from being commonly accepted in the eighteenth and nineteenth centuries. The main reasons for the doubt were: (a) the subtleness of the *PI* effect, which required special conditions and adequate instruments and methods of observation to guarantee its detection; and (b), the relative irreproducibility of the observations due to the infrequency of transits of Venus.

4.1 The Discussion of Venus' Atmosphere Between the 1769 and Nineteenth Century Transits

Most astronomers were not prepared to accept the observations of luminous phenomena reported during the eighteenth century transits as definitive proof of an atmosphere around Venus.

They were deterred by the fact that these observations were far from common (only about a dozen out of hundreds of observations) and by the discrepancies between different reports (not one, but four different phenomena: *PI-PIV*). At that time there also was no theory to explain refraction in Venus' atmosphere and predict what effects should be observable. As a result, most late eighteenth century and early nineteenth century astronomy textbooks either ignored the luminous effects seen during the transits (e.g. see Bailly, 1785: 109; Fergusson, 1785: 498) or else explained them as optical illusions (see Dunn, 1774: 32). The Lowndean Professor of Astronomy at Cambridge University, Roger Long (1680–1770) was one of the very few to support the presence of an atmosphere around Venus as a result of the transit observations, and he considered reports such as those by Chappe d'Auteroche, Dunn and Hirst as a proof (with some doubts about Chappe d'Auteroche's crescents), even though their evidence was not in accord with the understanding of the physics of such phenomena that prevailed at this time (see Long, 1774: 580).

In his *Astronomie*, France's foremost astronomer, Jérôme Lalande (1732–1807) was non-committal on the issue. He did not see any ring of light around Venus when he observed the 1761 transit, but he was aware of the observations by Chappe d'Auteroche, Fouchy, Le Monnier and Wargentin "... that would lead one to prejudge the atmospheres of the planets of the system, if the ring could not be explained by purely optical reasons ..." (Lalande, 1792: 561), an obvious reference to phenomenon *IV* which indeed is purely an optical illusion. Lalande's doubts were well known to and cited by Johann Hieronymus Schröter (1745–1816), Germany's leading observational astronomer, who offered somewhat less disputable evidence of a Venusian atmosphere during observations of the extension of the cusps of Venus by some 4.5° (see Schröter, 1792). However, Schröter's paper also reported observations of an atmosphere around the Moon (which is non-existent) and gigantic mountains on Venus which extended above its ca. 67-mile high atmosphere (which again was wrong). Meanwhile, England's foremost observational astronomer, William Herschel (1738–1822) strongly criticized Schröter's numerical estimates, but he did agree with his qualitative conclusion that it was the atmosphere of Venus which caused the extensions of the cusps (Herschel, 1793). One could not say that such an observation had convinced everybody, possibly because both observers made a number of very debatable claims in the course of their careers. We have already mentioned the excessively-high mountains on Venus supposedly seen by Schröter, while Herschel firmly believ-

ed that the Sun had a luminous atmosphere and solid habitable ground below, which sometimes was seen by looking down through sunspots (Kawaler and Veverka, 1981). The doubts and confusion over the issue of a Venusian atmosphere were quite obvious to others,³ and it is telling that John Herschel (1792–1871), William's son, used neither the transit observations of the luminous arcs/rings nor his father's and Schröter's reports on the extension of the cusps when he wrote about Venus in his popular textbook, *Outlines of Astronomy* (Herschel, 1849). Instead he merely inferred the existence of an atmosphere from the lack of permanent surface details—a qualitative argument that was easy to prove and by that time had been known already for about a century.

4.2 The Atmosphere of Venus During the Nineteenth Century Transits

Better instruments and methods of observation in the nineteenth century allowed many more astronomers to observe the arc of light (*PI*) at in-

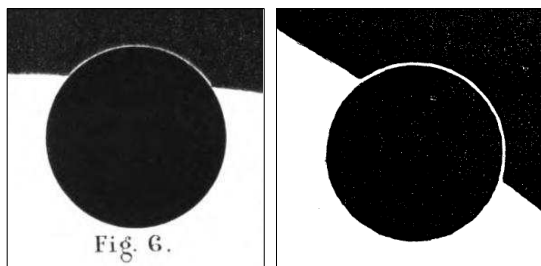


Figure 11: On the left is H.C. Russell's drawing of the arc of light around Venus during the egress phase of the 1874 transit (after Russell, 1883: Figure 6), and on the right is C.L. Prince's drawing of "...the planet's atmosphere shortly before internal contact ..." during the 1882 transit (after Prince, 1883).

gress and/or egress during the 1874 and 1882 transits.⁴ The appearance of the atmosphere at ingress or egress was not a surprise anymore, and many observers studied the phenomenon in detail. In Australia, Sydney Observatory Director, Henry Chamberlain Russell (1836–1907) observed the 1874 transit with a 12½ ft refractor of 11.5 inches aperture (reduced to 5 inches for the visual observations) and a magnification of 100× (Russell, 1883). He experimented with filters of different strengths and colors, and had no difficulty observing the arc (see Figure 11).

Many of Russell's New South Wales colleagues left quite detailed descriptions and drawings of the phenomena observed at ingress and egress (for details see Orchiston, 2004), and most of these were published by Russell (1883) in his report of observations by professional and amateur astronomers and Government and University of Sydney scientists associated with Sydney Observatory's 1874 transit program. It is interesting that many of the drawings included in

this report are exactly like, or very close, to what Lomonosov and others saw during the eighteenth century transits. For example, drawings similar to Lomonosov's *PI* (the arc, full or partial) were provided by A.W. Belfield (Figures 1 and 3 in Plate IV), Captain Arthur Onslow (Figures 14 and 15 in Plate II), Archibald J. Park (Figures 5 and 6 in Plate IV), Russell (Figures 6 and 7 in Plate II) and L. Abington Vessey (Figures 3, 4, 5, 11 and 12 in Plate III). Robert Ellery (1827–1908), the Director of Melbourne Observatory, also published drawings reminiscent of *PI* (see Ellery, 1883: Figures 1, 2 and 14 in Plate I), as also did Australia's foremost nineteenth century astronomer, John Tebbutt (1834–1916; see Orchiston, 2002) who observed the transit from his privately-maintained Windsor Observatory near Sydney (see Tebbutt, 1883: Figures 8, 9 and 13 in Plate IV). However, in most of these drawings the thickness of the arc is significantly smaller than that observed during the eighteenth century transits, which is a clear sign that the astronomers were using larger aperture telescopes. Still there were some contradictory observations. For example, the experienced New South Wales amateur astronomer William J. Macdonnell (1842–1910) observed an arc as thick as the one shown in Bergman's 1761 drawings, but with some subtle ray-like structure which is reminiscent perhaps of the rays reported by Rittenhouse in 1769 (see Russell, 1883: Figure 7 in Plate IV). Meanwhile, during the very early moments of the egress, Sydney University's Professor Archibald Liversidge (1846–1927) saw the part of Venus that already was off the Sun's disc fully illuminated (see Russell, 1883: Figures 16 and 17 in Plate II), a phenomenon that probably is similar to Lomonosov's *PIII*. Some observers reported seeing a broadening of the luminous arc in Venus' polar regions, often in the form of a small, broad-based inward-pointed pyramid.

Many more similar reports were published after the transit of Venus on 6 December 1882 (e.g. see Eastman, 1883; Langley, 1883; Prince, 1883), and an attempt to develop further the theory of refraction of solar rays in the atmosphere of Venus during the transit was published by Johns Hopkins University's Professor Charles Sheldon Hastings (1848–1932) in 1883. It is noteworthy that Otto Wilhelm von Struve (1819–1905), the Director of Pulkovo Observatory in St. Petersburg, attempted to observe the 1874 transit with old Dollond telescopes that previously were used by Russian expeditions during the eighteenth century transits (see Abalakin et al., 2009).

4.3 Twentieth Century Discussions, and the 2004 Transit

There were no transits in the twentieth century,

so most of the discussions on the subject of the atmosphere aureole were based on reports from previous transits. At the same time, knowledge about the atmosphere of Venus expanded immensely due to new methods of research. Spectroscopy, radio astronomy and space probes uncovered many mysteries of Venus' CO₂-dominated atmosphere, and scientists were able to learn a lot more in the second half of the twentieth century than in the previous 350 years of telescopic observations (see Marov and Green- spoon, 1998). The circumstances surrounding the discovery of the atmosphere in 1761 were discussed by several researchers, including O. Struve, V. Sharonov, F. Link and A.J. Meadows. None of these astronomers saw the phenomenon themselves, and often they based their interpretations of the eighteenth century reports on their own understanding of the various effects in the planet's atmosphere. Many were not aware of the details of Lomonosov's paper as it had not been properly translated into English. Nevertheless, in general we can see a growing appreciation of Lomonosov's discovery, and his observation of the arc during the transit (phenomenon *PI*) was eventually named the 'Lomonosov Effect' (Sharonov, 1952a) or 'Lomonosov's Phenomenon' (Sharonov, 1952b; cf. Link, 1969) and, later, 'Lomonosov's arc' (Tanga, et al, 2011; 2012).

Otto Struve (1897–1963), a US astronomer and grandson of Otto Wilhelm Struve (Director of Pulkovo Observatory in St. Petersburg at the end of the nineteenth century), in 1954 published a very sympathetic article about Lomonosov in *Sky and Telescope* magazine where many astronomical achievements and inventions of the Russian were described (Struve, 1954). As for the discovery of Venus' atmosphere, the article presented a mixed bag of correct and incorrect statements and guesses. First of all, it claimed that

... for unknown reasons the article by Lomonosov was not published during his lifetime and it has remained unknown to most historians of science ... it was printed in Vol. V of Lomonosov's collected works, edited by M.I. Sukhomlinov in 1891-1902.

In fact, Lomonosov's paper was published during his lifetime and was widely disseminated, and it was reprinted many times (see the discussion in Section 2). Moreover, the German translation of the paper was available in the USA (e.g. at Cornell University library), and was known to American scientists long before Struve wrote his paper (e.g. see Smith, 1912). Secondly, Struve wrote:

The question still remains whether the blister on the edge of the Sun, seen by Lomonosov, actually represented sunlight passing through Venus' atmosphere that was either refracted in that atmosphere or underwent considerable

scattering by small particles ...

Then Struve questioned Sharonov's (1952a) analysis which attributed the arc ('blister') to refraction, and stated

... of course, it is now known that when Venus is several degrees from the Sun its atmosphere can be observed as a faint, narrow luminous ring around the planet. This faint luminosity was not observable in the telescopes of Lomonosov's day. However, when Venus is entering or leaving the Sun at transit, the ring is more conspicuous. David Rittenhouse saw it at the 1769 transit ... but this phenomenon is not bright enough to account for Lomonosov's observation.

Here we see that Struve mistakenly tended to believe that the arc was due to scattering. Nor was he aware that Rittenhouse saw rather bright light as well, and that in 1761 a dozen other astronomers (before Rittenhouse) observed the arc. Finally, Struve put forward as a more convincing argument for phenomenon *PII*,⁵ which we now consider less convincing than seeing the arc, concluding:

... it is more difficult to dispose of his [Lomonosov's] observations of the haziness at the edge of the Sun when the planet was just outside the limb ... Lomonosov's intuition has since been proven sound, that Venus has an atmosphere and is physically similar to the earth.

Contrary to his Yerkes Observatory colleague, Gerard P. Kuiper (1905–1973), who thought that what Lomonosov observed was the 'black drop effect' (Menshutkin, 1952: 148), Struve correctly pointed out that Lomonosov did not report seeing that phenomenon (*PV*). Struve's reservations concerning Lomonosov's discovery were caused by his own interpretation of the effects of Venus' atmosphere that he thought should be observed during the transit—but these were not completely correct according to modern knowledge.

Vsevolod Sharonov (1901–1964), a prominent Soviet astronomer and Director of the Leningrad University Observatory, published a series of papers on Lomonosov's arc. In Sharonov (1952a) which he based on Lomonosov (1761a), he computed the horizontal refraction, ω , in the corresponding layer of Venus' atmosphere, the "... transparent gaseous layer above the cloud-like aerosol layer which hides the surface of Venus ...", to be less than 22". That conclusion comes from his optical analysis of the formation of the arc as a refracted image of sunlight and the fact that in most cases reported by Lomonosov and other transit observers the arc formation at ingress starts with horns or whiskers near the Sun's limb and spreads over the rest of Venus' disc that is then off the Sun (with the order reversed at egress)—see the left-hand dia-

gram in Figure 12. Asymmetry and/or irregularities in the light distribution over the arc could be explained by different conditions of the gases in the corresponding regions of the atmosphere or by differences in the altitude of the upper boundary of the cloud cover. In such cases, the larger horizontal refraction angle ($\omega > 22''$) results in the Sun's image first appearing at the point on the limb of the planet which is diametrically opposite to the limb of the Sun, and then spreading along the limb and encircling the planet with a luminous fringe (see the right-hand diagram in Figure 12).

Sharonov (1958: 302) explains:

At $\omega < 16''$ the cone of rays refracted in the atmosphere of Venus is divergent; at $22'' > \omega > 16''$ the cone converges and its apex is beyond the Sun. In both instances the luminous rim is formed according to the conditions of the first case ... [see the left-hand diagram Figure 12, below]. At $\omega = 22''$ the annular fringe appears instantaneously, and at $\omega > 22''$ the focus is lo-

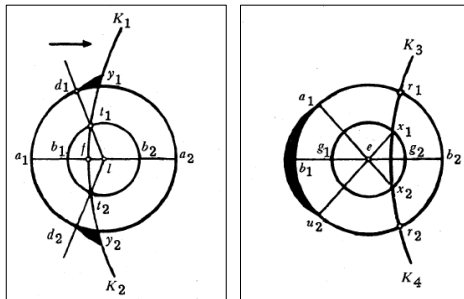


Figure 12: Sharonov's analysis of the angle of horizontal refraction, ω , where K_1, K_2 and K_3, K_4 indicate the solar limb. The diagrams show the formation of Lomonosov's arc as projected on the celestial sphere. The left-hand and right-hand diagrams relate to $\omega = 22''$ and $\omega > 22''$ respectively (after Sharonov, 1958: 300).

cated nearer than the Sun, which corresponds to the second case of the formation of the luminous rim ... [see the right-hand diagram in Figure 12, above]. The published data concerning the Lomonosov phenomenon observed during the transits of 1761, 1769, 1874 and 1882, show that the fringe appeared to form either instantaneously or gradually with "whiskers" growing from the solar limb (first case). Hence, the horizontal refraction in the atmospheric layer adjacent to the nontransparent layer of the cloudlike aerosol of Venus never exceeds $22''$... Thus we reach the conclusion that the horizontal refraction in the transparent part of the atmosphere of Venus ranges between 15 and $20''$ under ordinary conditions; sometimes the horizontal refraction increases inordinately, which can be explained either by specific physical conditions of the gas in the corresponding regions of the atmosphere (temperature, pressure, composition), or by differences in the altitude of the upper boundary of the cloud cover. The second explanation is more plausible.

Sharonov (1952b; 1955; 1960) also performed a detailed analysis of the circumstances of Lomonosov's discovery (in particular, his leading role in organizing the Russian transit observations in 1761, altercations with another St. Petersburg Academician, F.U.T. Epinus, and the exact dates of his 1761 publications), and he made a detailed comparison of many eighteenth century transit reports of aureoles, by Russian (Lomonosov and Rumovsky), Swedish (Bergman, Mallet, Melander, Planman, Stroemer and Wargentín), French (Chappe d'Auteroche, de-Mason, Fouchy and Le Monnier), English (Dunn) and American (Rittenhouse) astronomers. He pointed out the distinct difference between Lomonosov's phenomenon *PI* (the arc) and optical illusions (*PIV* and *PV*), but was undecided on *PIII* (the hair-thin irradiance close to internal contact) which he thought could possibly be incorrectly described, or could be real (as similar radiance was seen by others in 1874 and 1882). Sharonov agreed with D.M. Perevozshikov (1865) on Lomonosov's priority in the discovery on the basis of timely publication, completeness of the report and an understanding and correct explanation of the formation of the arc by refraction. Sharonov also was a key commentator on the subject in Lomonosov's *Complete Works* (Chenakal and Sharonov, 1955).

The Czech astronomer and founder and editor of *The Bulletin of The Astronomical Institute of Czechoslovakia*, Frantisek Link (1906–1984), independently analyzed old observations of the arc made during the transits of 1761 (all those listed in our Table 1 except Silberschlag, Hirst and Mallet), 1769 (a total of eight), 1874 (35) and 1882 (32). Link developed a theory for the optical formation of the refracted image of the Sun in Venus' atmosphere (the arc) similar to the one proposed by Sharonov, and he also argued that asymmetry of the light distribution over the arc was due to atmospheric conditions, in particular, greater brightness is observed at the polar areas of Venus, and he concluded that Venus rotates around its axis in the same direction as the Earth and other planets (which we now know to be incorrect). Among the deficiencies of Link's analysis of the old observations is that he omitted most of the details and did not comment on them except for short accounts of Chappe d'Auteroche (1761-1762) and Smith et al. (1769); and instead of including original drawings he presented simplified sketches of his own of selected observations made by just four eighteenth-century observers, Bergman, Chappe d'Auteroche, Rittenhouse and Wargentín). This led Link to reach several false conclusions, particularly relating to Lomonosov. For example, he wrote:

Lomonosov observed this transit with a small telescope (4½ ft. long) of bad optical quality

giving colored images outside the optical axis. Before the egress, when the limb of Venus was at a distance by $1/10$ of its diameter from the solar limb, Lomonosov detected at the solar limb a kind of swelling or blister becoming more distinct as the planet was approaching the egress. A short time afterwards the blister disappeared and the planet was visible without any special feature at the solar limb. Lomonosov explained this phenomenon by the refraction in the planetary atmosphere which is, according to him, equal if not more important than the terrestrial atmosphere. 113 years later the British astronomer Bigg-Wither observed a very similar phenomenon at the egress. When Venus was approaching the egress the planet seemed to push before it a kind of light ring. This feature was observed at the moment of the computed internal contact. Soon after, when the disk was outside the Sun, the ring in the form of a crescent was visible. Both Lomonosov's and Bigg-Wither's phenomena show a remarkable resemblance to each other and have probably the same origin in the irradiation which takes place on the limit of two areas of very different brightness observed under bad conditions. In addition, the explanation given by Lomonosov is not valid as it pre-supposes the refracting atmosphere at the height of $1/10$ of diameter (= 1200 km), which is impossible, thus making it clear that Lomonosov never saw an atmospheric phenomenon which is different from the appearance observed by him and Bigg-Wither. We feel 1) that Lomonosov proposed though somewhat incautiously an explanation by atmospheric refraction for the phenomenon observed by him which was, however, not of atmospheric origin, and 2) that his contemporaries having observed the true atmospheric phenomenon proposed independently but with more caution the same explanation. Neither Lomonosov nor any other astronomer has established (1761) any theory or brought to light any evidence to support their findings. The schematic outline of refraction presented by Lomonosov cannot, therefore, be considered as a form of theory and if it should be according to Sharonov, then this theory will have led to false conclusions about the importance of the Venusian atmosphere as quoted above. Hence we may admit under the denomination of Lomonosov's phenomenon only for the irradiation blister observed by him and later by Bigg-Wither and not for the true aureole observed in 1761 by nearly a dozen other astronomers. Thus, Sharonov, having collected and published a very copious documentation about Lomonosov's contribution, has not convinced the present author of its scientific value, neither has it convinced Struve who, some years ago, carried out an independent investigation; he, too, came to similar conclusions. (Link, 1969: 215-216).

Let us go through Link's misconceptions one by one: firstly, although Link was not aware of Nemiro's 1939 publication which asserted the

high quality of Lomonosov's telescope (a Dollond achromat) he still could have inferred this from the thickness of the arc observed by Lomonosov (the smallest among all the observers in 1761). Secondly, the reference to the $1/10^{\text{th}}$ of Venus' diameter distance was made to the disturbed edge of the Sun, as indicated in Lomonosov's *Fig. 3* and especially *Fig. 4* (see our Figure 1), and one can see in the latter that the leading edge of Venus is about $1/10$ of its diameter beyond the line where the unperturbed limb of the Sun would be, and the distance between the leading edge of Venus and the perturbed Sun's limb (the outer edge of the 'blister') varies from about $1/10^{\text{th}}$ of Venus' diameter (in *Fig. 3*) to about $1/15^{\text{th}}$ (in *Fig. 4*). The most outrageous claim, though, is the similarity between Lomonosov's observations and those made by Captain A.C. Bigg-Wither (1844–1913), an engineer with the Indus Valley Railway who was living in Multan in what is now Pakistan (see Kapoor, 2014). Figure 13 shows the original 1874

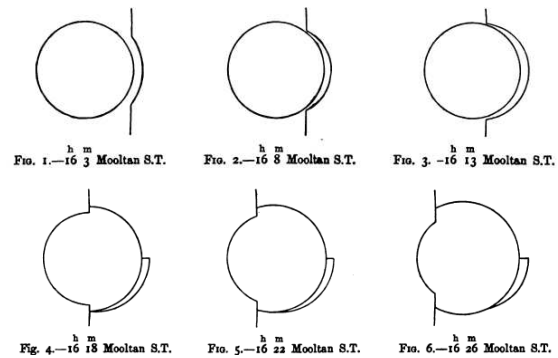


Figure 13: Bigg-Wither's drawings of the 1874 transit showing his observations at egress (after Bigg-Wither, 1883: 98-99).

drawings of Bigg-Wither (1883: 98-99), and one can see that contrary to Lomonosov's observations (and many others), Bigg-Wither's has two remarkable oddities: an arc which is thick in the middle and very thin at the ends touching the Sun (Figs. 2 and 3) and the reduction of the arc to one half during the later stage of egress (Figs. 4 to 6). It is very hard to find any reasonable explanation for these observations (as admitted by the observer himself),⁶ and even harder to suggest that they are in any way similar to Lomonosov's *Fig. 4*. Again, as Link presented modified and overly-simplified versions of Lomonosov's *Figs. 3, 4* and *5* side-by-side with only the first three of Bigg-Wither's (also slightly modified) in his book, one might think that he believed there were similarities between Bigg-Wither's *Fig. 1* and some of Lomonosov's drawings. But he could not have been paying attention to outstanding differences between the other images. Also, it is hard to explain Link's reference to Struve, who first of all was uncertain about the physics of Lomonosov's arc

(was it caused by refraction or scattering?) and secondly, was not willing to draw any firm conclusions—let alone express a flat denial. Sharonov (1960) pointed to these obvious flaws in Link's arguments, and we tend to agree that it is hard to consider them seriously.

In 1966 the noted University of Leicester historian of science Professor A.J. (Jack) Meadows published a much more systematic analysis based on a true scientific evaluation. First of all, he presented original plates of Lomonosov's figures (and, for comparison, a plate from the later publication by Bergman (1761-1762)); gave an English translation of the most relevant part of Lomonosov's 1761a paper, and correctly identified 15 July 1761 (in the Julian calendar) as the date of this pioneering publication. Despite confusion over what "... the 1/10th of the Venus diameter distance ..." refers to (just like F. Link—see above), he considered the disturbance of the solar limb shortly before the ingress (*PII*) as a true indication of the atmosphere of Venus; confirmed in 1769 by Hirst; and concluded that "... Lomonosov's description of refraction in the hypothetical atmosphere of Venus was undoubtedly the best available at the time." (Meadows, 1966: 125). He considered that the appearance of the line of light at the second contact (*PIII*) was an optical illusion, which also was witnessed by several observers of the nineteenth century transits. Many observations of the arc and/or aureole were (even briefly) discussed in this paper (e.g. the 1761 transit reports by Bergman, Chappe d'Auteroche, Desmares, Dunn, Ferner, Fouchy, Hirst, Le Monnier, Mairan, Planman, Rumovsky and Wargentin, and the 1769 transit reports by Dunn, Dollond, Hirst, Hitchins, Horsley, Mairne and Maskelyne). Meadows also attempted to sort them out and separate optical illusions (e.g. observations of the aureole during the whole passage across the Sun—phenomenon *PIV*) from true atmospherically-induced effects (i.e. *PI*, the arc). Still, there were some misidentifications. For example, Dunn's aureole observation was considered to be similar to the effect reported by Bergman, and Chappe d'Auteroche was cited as giving the most exact reference to an atmosphere, while he obviously did not. Meadows (*ibid.*) then considered the reaction among astronomers after the eighteenth century transits and noted that

... it is evident that most astronomers were not prepared to accept the evidence from the transits as certain proof of an atmosphere round Venus. They were deterred by the discrepancies between different observers ... [and] the reports conflicted so greatly.

Unfortunately, Meadows in 1966 did not try to address the reason for the discrepancies—something that would only be fully understood almost

half a century later (see Shiltsev et al., 2013)—merely concluding that "... in this sense, nobody discovered the atmosphere of Venus."

Of course the first of the two transits of the twenty-first century, on 8 June 2004, represented a huge step forward for observers, as modern imaging technologies were available for the first quantitative analysis of the atmosphere-induced aureole and its comparison with a simple refraction model and with observations of the 'Lomonosov arc' obtained in the past. A number of images of the aureole captured by CCD cameras through relatively large and good-quality telescopes were analyzed, where it was noted that

... visual observers under good sky conditions and employing a magnification higher than ~150x had no particular difficulty in identifying the bright aureole outlining the Venus disk between 1st and 2nd contact, while it was crossing the solar limb ... Skilled observers immediately noticed the non-uniform brightness of the aureole along the planet disk. (Tanga et al., 2012: 208).

Yet analysis of the 600 or so entries from about 80 amateur observers located in Russia and Ukraine and posted on the forum <http://www.astronomy.ru/forum/index.php/topic,4790.0.html> revealed far from uniform success in seeing the aureole, even in favorable atmospheric conditions: only 30 people reported observing the arc, using instruments with apertures varying from 40 mm to 312 mm, and magnifications from 33x to 200x. One person indicated that it was only when he exchanged a standard M5.0 solar filter for a much weaker one that he was able to detect the arc.

5 CRITICISM OF THE PAPER BY PASACHOFF AND SHEEHAN

A few months before the 2012 transit, the American astronomers Professor Jay Pasachoff and Dr William Sheehan (2012a) published a paper in this journal where they bluntly denied Lomonosov's observations, arguing that his discovery was an erroneous claim. They then attempted to assign the credit to other observers. Subsequently, this paper stimulated extensive discussion by members of the History of Astronomy Discussion Group (HASTRO-L).

Here we consider only the major issues (with the page numbers generally referring to Pasachoff and Sheehan's 2012a paper).⁷

(1) Lomonosov's telescope was claimed to be inadequate, based on a misreading of the source material and ignorance of the facts on the subject. For example, on page 5, it is said that Lomonosov "... used a non-achromatic refractor ... that consisted of little more than two lenses (objective and eyepiece)." Later, the same authors

state:

We think that what he [Lomonosov] saw was an artifact of his relatively primitive and small telescope rather than the aureole that is sunlight refracted toward Earth by Venus' atmosphere ... (Pasachoff and Sheehan, 2012b: 11).

These claims are not correct, as shown in Section 2 above where it is established that Lomonosov's telescope was a good quality Dollond refractor with two lenses in the objective. There is also indirect evidence. The description "... two lens telescope ..." is found in all translations which simply follow word-for-word the language of the original translations (Marov, 2005: a "... two-lenses tube ..."; and Shiltsev, 2012b: a "... telescope with two glasses ..."). Although there is some ambiguity in this description, it almost certainly refers to the achromatic objective of the telescope, not the telescope and eyepiece together, because in 1761 it was possible that a single objective could be used but an eyepiece with a single lens would have been unusual and inadequate. Multiple-element eyepieces were commonly used long before the mid-1700s, and it is hard to believe that a serious and well-connected astronomer like Lomonosov—a member of the ruling Chancellery of one of the best-funded scientific academies in the world at the time—would have used an inferior eyepiece for a major observation such as the 1761 transit. Therefore, it is hard to doubt that the term "two lenses" describes the objective. It is unclear why Pasachoff and Sheehan (2012a) hedged their bets by describing Lomonosov's telescope as "... little more than ..." two lenses. This incorrect description was then used as the basis for a sweeping rejection of his observations, because of "... the poor quality of this instrument."

(2) On page 6: "... Lomonosov, in particular, makes clear that his own instrument was of marginal quality. It clearly suffered from chromatic aberration." All refracting telescopes of that era exhibited chromatic aberration, especially during solar observations. The 2012 replication of Lomonosov's observations also produced a similar reference: "... the color fringe effect was noticeable only at the edge of the field of view (at approximately $\frac{3}{4}$ from the center of the optical axis) ..." (Koukarine, et al., 2012). It seems that Lomonosov was just demonstrating that he was a careful observer when he noted this problem, which most probably was caused by aberrations in the ocular (Petrunin, 2012), and he effectively addressed this by centering his telescope on Venus:

... during the entire observation the tube was permanently directed in such a way that Venus was always in its center, where its [Venus'] edges appeared crispy clear without any colors. (Shiltsev, 2012b).

(3) A revealing argument is made on page 6 that telescopes of that era were generally inadequate to the task because

... since the total apparent angular height of Venus' air is only about 0.02 arc seconds, it is, despite its brilliance, a delicate feature, and would presumably have been beyond the range of most eighteenth century observers with the small instruments available to them.

The first part of this statement seems to reflect a misunderstanding of the physics of the phenomena—indeed, the minuscule angular size of the object does not prevent it from being detected (think, for example, of point-like stars); it is the total brightness of the diffracted image that matters. As for the second part of the sentence, it is even more confusing as the authors themselves later note similar observations of the arc which were made in 1761, by Chappe d'Aueroche, Bergman and Wargentin (and, as we have shown above, many others), and accepted them as genuine. The arc indicating Venus' atmosphere is visible in telescopes smaller than that used by Lomonosov, as was shown by various groups in the USA, Russia and Canada during the 2012 transit (and for a discussion of the 2012 observations see Section 6, following, and references therein).

(4) Pasachoff and Sheehan seem to have misread their own translation of Lomonosov's report and are preoccupied with the "... hair-thin luminous sliver ..." seen by Lomonosov at second contact (phenomenon *PIII*), concluding that it "... refers to nothing more than the flash of sunlight between the trailing limb of Venus and the limb of the Sun marking the end of second contact." (page 7). We agree that such a phenomenon alone can hardly be used to conclude the existence of a Venusian atmosphere, and this is exactly what Lomonosov himself avoided referring to when making his claim. Indeed, this luminous sliver seen at ingress is not even illustrated in Lomonosov's figures. Instead, Lomonosov describes phenomena *PI* and *PII* (the arc, and the smeared Sun's limb at the points of the first and fourth contacts) as evidence of Venus' atmosphere, arguments which have been neglected by Pasachoff and Sheehan.

(5) On page 7 Pasachoff and Sheehan write that "... at no time did Lomonosov report any phenomena that resembled the phenomena seen during the transits of 2004 and 2012, with an arc above Venus' external limb ...", but this statement is incorrect as most of the observations of the twenty-first century transits of Venus (and, in that regard, of other transits) were qualitatively similar, as a comparison of Lomonosov's *Fig. 4* (see our Figures 1 and 2) and the above discussion shows.

In conclusion, there is no basis for Pasachoff and Sheehan's (2012a: 7) claim that

... Lomonosov's observational data were flawed, [and] his detailed geometrical treatment also proves to have been spurious ... We have now shown definitively that ... Lomonosov arrived at the correct conclusion but on the basis of a fallacious argument.

Moreover, the successful replication of Lomonosov's observations during the 2012 transit of Venus raises further doubts about these statements, and Pasachoff and Sheehan's attempts to assign discovery priority to other observers (e.g. Chappe d'Auteroche, or Rittenhouse, or Wargentin and Bergman) are unwarranted.

6 EXPERIMENTAL REPLICATION OF LOMONOSOV'S DISCOVERY DURING THE 2012 TRANSIT OF VENUS

Lomonosov's discovery was experimentally replicated during the transit of Venus on 5-6 June 2012. A thin arc of light on that part of Venus off the Sun's disc during the ingress has been successfully detected with original eighteenth-

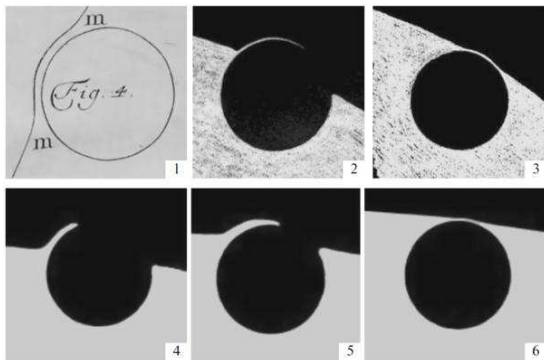


Figure 14: 1) shows 'Lomonosov's arc', the bulge on the Sun's limb at egress noted in 1761 (after Lomonosov, 1761b); 2) and 3) show 2012 observations at Lick Observatory with a 67-mm antique Dollond achromatic refractor and a weak filter; 4) to 6) show 2012 observations in Illinois with a 40-mm antique Dollond achromatic refractor and weakly-smoked glass filter (left), at 17:16, 17:19 and between 17:21 and 17:22 (all times in CST = UT-5) (after Kukarin, et al, 2013: 529).

century Dollond achromatic refractors similar to that deployed by Lomonosov and with his experimental techniques carefully emulated (e.g., lightly-smoked glass filters, and periodic rest for the eyes to maintain sensitivity) (see Koukarine, et al., 2012; Kukarin, et al., 2013). The experimental re-enactments resulted in successful detection of the aureole effect, a thin arc of light on that part of Venus off the Sun's disc when the planet was in transit—see Figure 14.⁸ Despite having small apertures by modern standards, the old achromatic refractors were found fully adequate for the task of detecting the light refracted around Venus. Several factors combined to allow replication of Lomonosov's discovery

of the Venusian atmosphere. The Dollond achromats were found to be of remarkably good quality, and had sufficiently large apertures and suitable filters. Care was taken to reduce the stray light and to assume comfortable viewing postures that would minimize eye strain. Simultaneous observations with high-quality modern doublet refractors with apertures as small as 50 mm revealed the aureole, and demonstrated that systems designed with modern software, employing modern optics and coatings did not significantly out-perform the older instruments (Rosenfeld et al, 2013).

The replication also allowed us to understand the inconsistent success in the detection of Lomonosov's arc, now and in the past (Shiltsev et al., 2013). When observed through a telescope, the brightness of the arc is determined by how much its width is spread due to diffraction, an effect inversely proportional to the aperture diameter, and to atmospheric turbulence (which is independent of the telescope's parameters). As with any extended object, the brightness of the arc and the Sun should not depend on the optical system's magnification. Observations of the arc with modern doublet refractors and a standard 1/100 000 filter in Saskatchewan (Rosenfeld et al., 2013) supported the above analysis and confirmed that aperture diameter plays the critical instrumental role in the detection of the aureole, while the magnification used was found to be a less important variable. Because of the non-linear response of the human eye, the optimal filter to be selected depends on the observational goal. To see the arc around Venus, the weakest filter that allows for comfortable and safe viewing should be used. A stronger filter would be better suited for studying the Sun over a long period, but it would reduce the arc's perceived brightness so much that the arc would be invisible against the background. The use of attenuating filters makes ambient glare from sunlight while viewing at the eyepiece a relatively large nuisance; it is important, therefore, to reduce stray light.

Unlike Lomonosov, most observers in the eighteenth century directed their attention exclusively to timing the contacts of Venus with the solar disk. The longer observation periods needed to achieve that goal demanded stronger filters than that used by Lomonosov for detection of the arc. Finally, not all of the instruments used at that time could match the optical quality of the Dollond achromats.

7 CONCLUSIONS

As shown above, during observations of the transits of Venus there were several optical phenomena that could be attributed to the atmosphere of the planet: an arc of light around that

part of Venus that was off the Sun's disc at the ingress and egress; the blurriness of the Sun's limb at the times of the 1st and the 4th contacts; a thin bright radiance close to the times of the internal contacts; and the circular aureole around Venus when it was fully on the Sun's disc. The first of these, the 'arc', is caused by refraction of sunlight in the Venusian atmosphere, and was observed and described in similar terms by a dozen astronomers in 1761 and by many during the following transits, including the last one, in 2012. Mikhail Lomonosov stands out among the observers as he was the first to publish a scientific report of the phenomenon, understand it was due to refraction, and conclude from this that Venus possessed an atmosphere. As he providing the correct physical explanation for this and a detailed description of his methods of observation, astronomers were able to replicate his discovery more than two and a half centuries later. Our analysis of the 1761 observations of the transit and subsequent discussions show that the use of the term 'Lomonosov's arc' seems appropriate as he is the one who should be credited with the discovery of Venus' atmosphere.

Lomonosov's discovery was experimentally replicated during the 5-6 June 2012 transit of Venus when a thin arc of light on that part of Venus lying off the Sun's disc during the ingress was successfully detected with original antique telescopes similar to the one used by Lomonosov. The replication also shed additional light on why detection of the aureole was so capricious in the past, and it showed once again that a great discovery involves deep insight into physics on the part of the discoverer, the right instruments and techniques, and a little luck. From what we have learned through restaging his historic 'enlightenment' experience, Lomonosov seems to have been the only one to discover the Venusian atmosphere not by mere accident but by designing an experimental protocol that made it possible.

8 NOTES

1. N.I. Nevskaya (1973; 2000: 152-156) suggests that Lomonosov's thinking about possible experimental techniques to detect atmospheres of planets began even earlier, in the mid-1740s, during collaborative astronomical studies under the renowned French astronomer, Joseph-Nicolas Delisle (1688–1768), who was Professor of Astronomy at the St. Petersburg Academy from 1725 to 1747.
2. Dunér (2013: 158) claims that Lomonosov ... was neither the first, nor the only one, to conclude that the phenomena were caused by a Venusian atmosphere. Bergman and others published their results first.

This claim simply is not true. As we have seen, Lomonosov actually began writing his first paper (in Russian) about the transit the day after the event, and this paper, and his later one, in German, were both published in 1761, in July and August respectively. Only the papers by Hellant, Strömer et al. and Le Monnier also were published in 1761, the first two in the third quarterly issue of *Kungliga Vetenskapsakademiens Handlingar* for that year (i.e., no earlier than July), while Le Monnier's paper was published even later in the year. In contrast, the papers in the *Philosophical Transactions of the Royal Society* by Bergman and Wargentin only appeared in 1762.

3. One can add that even at the very end of the nineteenth century the confusion over the cusp observations was quite valid. For example, H.N. Russell (1899: 298) concluded from his own observations that the elongation of the cusps was significantly smaller than reported by Schröter, only 1° 10', which indicated that Venus' atmosphere "... (could not be)...more than one third as dense or extensive as the Earth's."
4. Extensive literature exists on the circumstances surrounding and instrumentation used during the nineteenth century transit expeditions. For example, see the popular books by Lomb (2011), Maor (2000) and Sheehan and Westfall (2004) and bibliographies therein, or the series of papers in this journal: Clark and Orchiston (2004), Cottam et al. (2012); Débarbat and Launay (2006), Duerbeck (2004), Edwards (2004), Kapoor (2014), Lu and Li (2013), Orchiston and Buchanan (2004); Orchiston et al. (2000), Pigatto and Zanini (2001; 2004), Stavinschi, 2012; Sterken and Duerbeck (2004) and Tobin (2013).
5. Besides O. Struve, the phenomenon of an indistinct or hazy edge of the Sun at the point and time of Venus' entry onto the solar disc was considered and analyzed as a true atmospheric optical phenomenon by Professor A.I. Lazarev from the Vavilov State Optical Institute, St. Petersburg Russia. He wrote (Lazarev, 2000: 431):

... the first phenomenon [*P*II in our nomenclature – V. Shiltsev] was explained only in 1970 as the Fresnel reflection of the Sun from the Venusian atmosphere, which is especially strong at small glancing angles, i.e., specifically under conditions where Venus is close to the solar disk (Lazarev, 1976). This explanation appeared after [Soviet cosmonaut] A.A. Leonov discovered the Fresnel reflection of the Sun from the Earth's atmosphere from the Voskhod-2 spaceship and subsequently explained it together with us. (Lazarev and Leonov, 1973).

6. Bigg-Wither (1883: 98-99) stated: "... I am unable to form an idea of the cause of this crescent."
7. There are also several minor factual errors such as reference being made to 2012 transit observations on page 7 (in a paper that was published *before* the 2012 transit); mix-ups with the contact numbering (page 7); the absence of an explanation as to why E. Stuyvert's observations of the 1882 transit were indicative of "... the double cause of the black drop ..." and how they relate to Lomonosov's observations when they are so different (page 7); the absence of critical discussions of the transit observations by Chappe d'Auteroche in 1761 and by Rittenhouse, Green and Cook in 1769 (pages 8-10); mis-spellings of the last names of F.U.T. Epinus (Aepinus) and V. Sharonov on pages 11 and 14; etc.
8. It is to be noted that weather did not cooperate with several of the observers who prepared antique achromats for the 2012 transit—their bad luck replicated that of more than a few eighteenth century observers. Some of them encountered cloud cover and did not observe the aureole (see Koukarine, et al., 2012), while others obtained ambiguous results due to significant air turbulence (see Nesterenko, 2013).

9 ACKNOWLEDGEMENTS

I greatly appreciate fruitful discussions with and input from Professor Robert Crease (SUNY), Dr Igor and Alfia Nesterenko (Budker Institute of Nuclear Physics, Novosibirsk, Russia and VEGA Observatory of Novosibirsk State University), Yuri Petrunin (Telescope Engineering Co, Golden, CO), Academician Anatoly Cherepaschuk and Dr Yuli Mentsin (Shternberg Astronomical Institute of Moscow State University), Professor Leonid Ksanfomaliti (Institute of Space Research of Russian Academy of Sciences, Moscow). I would like to thank Randall Rosenfeld (Royal Astronomical Society of Canada), Peter Abrahams (Antique Telescope Society) and Professor Wayne Orchiston (National Astronomical Research Institute of Thailand and founder and Chairman of the IAU Transits of Venus Working Group) for thoroughly reading the manuscript and valuable comments which helped to improve this paper. Finally, I am indebted to Dr Andreas Jansson (European Spallation Source lab, Lund, Sweden) and Dr Wolfram Fischer (Brookhaven National Laboratory, Upton, NY) for English translations of eighteenth century transit reports that originally were written in Swedish and German.

9 REFERENCES

- Abalakin V., Moskovchenko N., Polozhentsev D., 2009. Otto Vasilievich Struve, alias O.Σ. *Izvestiya Glavnoi Astronomicheskoi Observatorii v Pulkove*, 219, 5-37 (in Russian).
- Bailly, J.S., 1785. *Histoire de l'Astronomie Moderne Depuis la Fondation de l'École d'Alexandrie, jusqu'à l'époque de MDCCLXXXII. Tome Troisième*. Paris, DeBure (in French);
- Bergman, T., 1761-1762. An account of observations made of the same transit at Upsal in Sweden ... *Philosophical Transactions of the Royal Society*, 52, 227-230.
- Bigg-Wither, A.C., 1883. Observations of the transit of Venus, 1874, December 8-9, as observed at Mooltan, Punjab, India. *Memoirs of the Royal Astronomical Society*, 47, 97-99.
- Bond, P., 2007. *Distant Worlds: Milestones in Planetary Exploration*. New York, Springer.
- Chappe d'Auteroche, J., 1761-1762. Extract from a paper of Mons. De la Lande, of the Royal Academy of Sciences at Paris, to Mr. Gael Morris, of the transit of Venus, on the 6th June 1761, observed at Tobolsk in Siberia ... *Philosophical Transactions of the Royal Society*, 52, 254.
- Chappe d'Auteroche, J., 1762. *Memoire du Passage de Venus sur le Soleil ... faite à Tobolsk en Sibirie l'Annee 1761*. St. Petersburg, St. Petersburg Imperial Academy of Sciences (in French).
- Chappe d'Auteroche, J., 1763. Extrait du Voyage fait en Sibirie, pour l'observation de Venus sur le disque du Soleil, faite a Tobolsk le 6 Juin 1761. *Mémoires de l'Académie Royale des Sciences le Année 1761*, 337-372 (in French).
- Chappe d'Auteroche, J., 1768. *Voyage en Sibérie, fait par Ordre du Roi en 1761; Contenant les Moeurs, les Usages des Russes, et l'Etat actuel de cette Puissance; la Description Géographique & le Nivellement de la Route de Paris à Tobolsk*, etc. Paris, Debure (in French).
- Chenakal, V.L., and Sharonov V.V., 1955. Commentaries. In Vavilov and Kravets, *Volume IV*, 763-774 (in Russian).
- Chenakal, V.L., 1957a. Smaller observatories of the St. Petersburg Academy of Sciences in the XVIII century. *Historic Astronomy Studies*, 3, 261-428 (in Russian).
- Chenakal, V.L., 1957b. The design, construction and equipment of the first astronomical observatory of the St. Petersburg Academy of Sciences. *Historic Astronomy Studies*, 3, 429-451 (in Russian).
- Chenakal, V.L., Andreeva, G.A., Pavlova, G.E., and Sokolova, N.V., 1961. *Chronicles of the Life and Works of M.V. Lomonosov*. Leningrad, USSR Academy of Sciences (in Russian).
- Clark, B.A.J., and Orchiston, W., 2004. The Melbourne Observatory Dallmeyer photoheliograph and the 1874 transit of Venus. *Journal of Astronomical History and Heritage*, 7, 44-49.
- Comolli, L., 2004. 8 June 2004: Venus transit of the Sun. <http://www.astrosurf.com/comolli/cong5e.htm>
- Cottam, S., Orchiston, W., and Stephenson, F.R., 2012. The 1882 transit of Venus and the popularization of astronomy in the USA as reflected in *The New York Times*. *Journal of Astronomical History and Heritage*, 15, 183-199.
- D'Encausse, H.C., 2003. *L'Impératrice et l'Abbé: Un duel littéraire inédit entre Catherine II et l'Abbé*

- Chappe d'Aueroche*. Paris, Fayard (in French).
- Débarbat, S., and Launay, F. 2006. The 1874 transit of Venus observed in Japan by the French, and associated relics. *Journal of Astronomical History and Heritage*, 9, 167-171.
- Duerbeck, H.W., 2004. The German transit of Venus expeditions of 1874 and 1882: organization, methods, stations, results. *Journal of Astronomical History and Heritage*, 7, 8-17.
- Dunér, D., 2013. Venusians: the planet Venus in the 18th-century extraterrestrial life debate. In Sterken, C., and Aspaas, P.P. (eds.). *Meeting Venus. A Collection of Papers Presented at the Venus Transit Conference in Tromsø 2012*. Brussels, Vrije Universiteit Brussel and University of Tromsø. Pp. 145-167.
- Dunn, S., 1761-1762. Some observations of the planet Venus, on the disk of the Sun ... and certain reasons for an atmosphere about Venus. *Philosophical Transactions of the Royal Society*, 52, 184-195.
- Dunn, S., 1774. *A New and General Introduction to Practical Astronomy*. London.
- Eastman, J.R., 1883. The Florida expedition to observe the transit of Venus. *Science*, 1, 300-302.
- Edwards, P.G., 2004. Charles Todd's observations of the transits of Venus. *Journal of Astronomical History and Heritage*, 7, 1-7.
- Ellery, R.L.J., 1883. Observations of the transit of Venus. 1874, December 8-9, Colony of Victoria, Australia. *Memoirs of the Royal Astronomical Society*, 47, 31-47.
- Ferguson, J., 1785. *Astronomy. Explained Upon Sir Isaac Newton's Principles ... Seventh Edition*. London, W. Strahan, J. Rivington and sons, T. Longman.
- Ferner, B., 1761-1762. An account of the observations on the same transit made in and near Paris ... *Philosophical Transactions of the Royal Society*, 52, 221-225.
- de Fontenelle, B.L.B., 1686. *Entretiens sur la Pluralité des Mondes*. [A good modern translation is to be found in *Conversations on the Plurality of Worlds*. Hargreaves, H.A. (transl.). Berkeley, University of California Press (1990)].
- Fouchy, G., 1763. Observation du Passage de Vénus sur le Soleil ... *Mémoires de l'Académie Royale des Sciences 1763*, 99 (in French).
- García-Muñoz, A., and Mills, F., 2012. The June 2012 transit of Venus. Framework for interpretation of observations. *Astronomy & Astrophysics*, 547, id. A22, 1-11..
- Green, C., and Cook, J., 1771. Observations made, by appointment of the Royal Society, at King George's Island in the South Sea. *Philosophical Transactions of the Royal Society*, 61, 397-421.
- Grimm, B., Diderot D., Bland R., and Plumptre A., 1850. *Mémoires Politiques et Anecdotes. Volume 2*. Paris, Roye-Wolff (in French).
- Hastings, C.S., 1883. The phenomena presented by the atmosphere of Venus during a transit, *The Sidereal Messenger*, 1, 273-278.
- Hell, M., 1762. *Observatio Transitus Veneris ante discum Solis die 5ta Junii 1761*. Vienna, Joannis Thomæ Trattner (in Latin).
- Hellant, A., 1761. Venus i Solen, Observerad i Torne den 6 Junii 1761. *Kungliga Vetenskapsakademiens Handlingar*, 23,180-184 (in Swedish).
- Herschel, J., 1849. *Outlines of Astronomy*. London, Longmans.
- Herschel, W., 1793. Observations of the planet Venus. *Philosophical Transactions of the Royal Society*, 88, 201.
- Hirst, W., 1761-1762. An account of an observation of the transit of Venus over the Sun, on the 6th of June 1761, at Madrass. *Philosophical Transactions of the Royal Society*, 52, 396-398.
- Hirst, W., 1769. Account of several phaenomena observed during the ingress of Venus into the solar disc. by the Reverend W. Hirst, F. R. S. in a letter to the Astronomer Royal. *Philosophical Transactions of the Royal Society*, 59, 228-235.
- Kapoor, R.C., 2013. Indian astronomy and the transits of Venus. 1: the early events. *Journal of Astronomical History and Heritage*, 16, 269-286.
- Kapoor, R.C., 2014. Indian astronomy and the transits of Venus. 2: the 1874 event. *Journal of Astronomical History and Heritage*, 17, 113-135.
- Kawaler, S., and Veverka, J., 1981. The habitable Sun -- one of Herschel, William's stranger ideas. *Journal of the Royal Astronomical Society of Canada*, 75, 46-55.
- Kordenbusch, G.F., 1769. *Bestimmung der denkwürdigen Durchgänge der Venus durch die Sonne ...* Nurnberg, Kosten Der Raspischen Buchhandlung. (in German).
- Koukarine, A., Nesterenko, I., Petrunin, Y., and Shiltsev, V., 2012. Experimental Reconstruction of Lomonosov's Discovery of Venus' Atmosphere with Antique Refractors during the 2012 Transit of Venus. *arXiv preprint arXiv:1208.5286*
- Kukarin, A., Nesterenko, I., Petrunin, Y., and Shiltsev, V., 2013. Experimental replication of Lomonosov's discovery of Venus' atmosphere with antique refractors in 2012. *Astronomichesky Vestnik*, 47(6), 528-532 (in Russian – an English translation is in *Solar System Research*, 47, 487-490).
- Kuznetsova A., 2009. *The First Determinations of the Solar Parallax by Astronomers of the St Petersburg Academy of Sciences in 1761-1769*. St. Petersburg, Nestor-Istoria (in Russian).
- Lalande, F. de, 1792. *Astronomie. Volume 2. Third Edition*. Paris, P. Didot (in French).
- Langley, S.P., 1883. Observations of the transit of Venus 1882, December 6, made at the Allegheny Observatory. *Monthly Notices of the Royal Astronomical Society*, 43, 71-73.
- Lazarev, A.I. and Leonov, A.A., 1973. Specular reflection from Earth's atmosphere. *Soviet Journal of Optical Technology*, 40, 674 (in Russian).
- Lazarev, A.I., 1976. Estimates of the Fresnel reflection of the Sun from the atmosphere of Venus. *Astronomicheskii Vestnik*, 10, 190 (in Russian).
- Lazarev, A.I., 2000. Atmospheric optical phenomena on Venus. *Journal of Optical Technology*, 67, 431-435.
- Le Monnier, P., 1763. Observation du passage de Vénus sur le disque du Soleil. *Mémoires de l'Académie Royale des Sciences 1763*, 72-76 (in French).
- Link, F., 1959. Passages de Venus sur le Soleil. *Bulletin of the Astronomical Institutes of Czechoslovakia*, 10, 105-115 (in French).
- Link, F., 1969. *Eclipse Phenomena in Astronomy*. New York, Springer.
- Lomb, N., 2011. *Transit of Venus: 1631 to the Present*. Sydney, NewSouth Publishing.
- Lomonosov, M.V., 1759. *Meditationes de via Navis in*

- Mari Certius Determinanda Praelectae in Publico Conventu Academiae Scientiarum Imperialis Petropolitanae die VIII Mai, A.C. 1759 Auctore Michaele Lomonosow Consilario Academico. In Vavilov and Kravets, *Volume IV*: 187-319 (in Latin and Russian).
- Lomonosov, M.V., 1761a. *The Appearance of Venus On The Sun, Observed At The St. Petersburg Imperial Academy Of Sciences On May 26, 1761*. St. Petersburg, St. Petersburg Imperial Academy of Sciences (in Russian). [See also Vavilov and Kravets (IV), 361-376, and an English translation in Shiltsev, 2012b.]
- Lomonosov, M.V., 1761b. *Erscheinung der Venus vor der Sonne beobachtet bey der Kayserlichen Academie der Wissenschaften in St. Petersburg, den 26 May 1761. Aus dem Rußischen übersezt*. St. Petersburg, St. Petersburg Imperial Academy of Sciences (in German). [See also Lomonosov, M.W., *Ausgewählte Schriften in zwei Bänden*. Band 1: Naturwissenschaften. Berlin, Akademie-Verlag, Pp. 426-434.]
- Long, R., 1774. *Astronomy. Volume II*. Cambridge, printed for the author.
- Lu, L., and Li, H., 2013. Chinese records of the 1874 transit of Venus. *Journal of Astronomical History and Heritage*, 16, 45-54.
- Lur-Saluces, Marquis de, 1933. *Lomonossov, le Prodigeux Moujik*. Éditions Émile-Paul-Frères (in French).
- Lyubimov, N.A., 1855. Lomonosov as a physicist. In *Memoirs on January 12, 1885*. Moscow, Imperial Moscow University Press (in Russian).
- Maksutov, D., 1979. *Astronomical Optics*. Leningrad, Nauka.
- Mallet, F., 1766. De Veneris Transitu, per discum Solis, A. 1761, d. 6 Junii. *Philosophical Transactions of the Royal Society*, 56, 72-91 (in Latin).
- Maor, E. 2000: *Venus in Transit*. Princeton, Princeton University Press.
- Maraldi, M., 1763. Observation de la sortie de Vénus du disque du Soleil, faite à l'Observatoire Royal le 6 Juin 1761, au matin, *Mémoires de Mathématique et de Physique, Tirés des Registres de l'Académie Royale des Sciences pour l'Année 1761*, 76-77 (in French).
- Marov, M.Y., and Grinspoon, D.H., 1998. *The Planet Venus*. New Haven, Yale University Press.
- Marov, M.Y., 2005. Mikhail Lomonosov and the discovery of the atmosphere of Venus during the 1761 transit. In Kurtz, D.W. (ed.). *Transits of Venus: New Views of the Solar System and Galaxy*. Cambridge, Cambridge University Press. Pp. 209-219.
- Maskelyne, N., 1768. *Instructions Relative to the Observation of the Ensuing Transit of the Planet Venus over the Sun's Disk: on the 3d of June 1769*. London, W. Richardson and S. Clark.
- Maskelyne, N., 1769. Observations of the transit of Venus over the Sun, and the eclipse of the Sun, on June 3, 1769; made at the Royal Observatory ... *Philosophical Transactions of the Royal Society*, 58, 355-365.
- Maslikov, S., 2007. Lomonosov, Mikhail Vasil'evich. In Hockey, T, et al. (eds.). *Biographical Encyclopedia of Astronomers. Volume 1*. New York, Springer. Pp. 705-706.
- Meadows, A.J., 1966. The discovery of an atmosphere on Venus. *Annals of Science*, 22, 117-127.
- Melnikov, O.A., 1977. Lomonosov's astrophysical studies. In Karpeev, E.P., and Modzalevskij, A.I. (eds.). *Lomonosov: sbornik statei i materialov. Volume VII*. Moscow-Leningrad, USSR Academy of Sciences. Pp. 63-102 (in Russian).
- Menshutkin, B.N., 1952. *Russia's Lomonosov: Chemist Courtier, Physicist, Poet*. Princeton, Princeton University Press.
- Moore, P., 1961. *Astronomy*. London, Oldbourne.
- Nemiro, A., 1939. Astronomy Museum of Pulkovo Observatory. In *100 Years of Pulkovo Observatory*. Pulkovo, Pulkovo Observatory. Pp. 269-271 (written in 1939; published in 1945) (in Russian).
- Nesterenko, A., 2013. Did Lomonosov see the atmosphere of Venus? *Priroda*, 4, 11-19 (in Russian).
- Nevskaja, N.I., 1973. Joseph-Nicolas Delisle (1688-1768). *Revue d'Histoire des Sciences*, 26, 289-313 (in French).
- Nevskaya, N.I., 2000. *Sources on History of Astronomy in Russia*. St. Petersburg, Nauka (in Russian).
- Newcomb, S., 1891. Discussion of observations of the transits of Venus in 1761 and 1769. *Astronomical Papers Prepared for the Use of the American Ephemeris and Nautical Almanac*, II(V), 259-405.
- Orchiston, W., Love, T., and Dick, S.J., 2000. Refining the astronomical unit: Queenstown and the 1874 transit of Venus. *Journal of Astronomical History and Heritage*, 3, 23-44.
- Orchiston, W., 2002. Tebbutt vs Russell: passion, power and politics in nineteenth century Australian astronomy. In Ansari, S.M.R. (ed.). *History of Oriental Astronomy*. Dordrecht, Kluwer. Pp. 169-201.
- Orchiston, W., 2004. The nineteenth century transits of Venus: an Australian and New Zealand overview. *Journal of Astronomical Data*, 10, 219-308.
- Orchiston, W., and Buchanan, A., 2004. 'The Grange', Tasmania: survival of a unique suite of 1874 transit of Venus relics. *Journal of Astronomical History and Heritage*, 7, 34-43.
- Orchiston, W., 2005. James Cook's 1769 transit of Venus expedition to Tahiti. In Kurtz, D.W. (ed.). *Transits of Venus. New Views of the Solar System and Galaxy*. Cambridge, Cambridge University Press. Pp. 52-66.
- Pasachoff, J.M., and Sheehan, W., 2012a. Lomonosov, the discovery of Venus' atmosphere, and the eighteenth-century transits of Venus. *Journal of Astronomical History and Heritage*, 15, 3-14.
- Pasachoff, J.M., and Sheehan, W., 2012b. Did Lomonosov see the Venusian atmosphere? *Physics Today*, 65 (11), 11-12.
- Perevozshikov, D.M., 1865. Lomonosov's works in physics and physical geography. *Raduga*, 4, 176-201 (in Russian).
- Petrinin, Y., 2012. The telescope which discovered the Venus' atmosphere. See: <http://telescopehistory.wordpress.com/2012/07/07/the-telescope-which-discovered-the-venuss-atmosphere/>
- Pigatto, L., and Zanini, V., 2001. Spectroscopic observations of the 1874 transit of Venus: the Italian party at Muddapur, eastern India. *Journal of Astronomical History and Heritage*, 4, 43-58.
- Pigatto, L., and Zanini, V., 2004. The 1882 transit of Venus observed in Italian observatories. *Journal of Astronomical History and Heritage*, 7, 18-24.
- Planman, A., 1768. A determination of the solar parallax attempted, by a peculiar method, from the observations of the last transit of Venus ... *Philosophical Transactions of the Royal Society*, 58, 107-

- 127.
- Prince, C.L., 1883. Note on the transit of Venus, 1882, Dec. 6. *Monthly Notices of the Royal Astronomical Society*, 43, 278.
- Röhl, L.H., 1762. *Observatio Astronomica Transitus Veneris sub Disco Solis Gryphiæ anno 1761. d. 5 Jun. habita*. In Mayer, A., (ed.). *Observationes Veneris Gryphiswaldenses quibus adiecta est M. Lamb. Henr. Röhlj ... Observationis suae de Transitu Veneris per Solem Expositio*. Gryphiswaldae, A.F. Röse. Pp. 1-13 (in Latin).
- Röhl, L.H., 1768. *Merkwürdigkeiten von den Durchgängen der Venus durch die Sonne*. Greifswald, A. F. Röse (in German).
- Rosenfeld, R., Beckett, C., O'Brien, M., Danielson, J., Sheppard, R., and Greenham, P., 2013. The Venus aureole effect: minimum aperture for visual detection. *Journal of the Royal Astronomical Society of Canada*, 107, 29-34.
- Rumovsky, S., 1762. Explanation of Selenginsky's observations during the transit of Venus. In *Accomplished Triumph in the Moscow Coronation ... of Empress Catherine Alekseevna ... 23 of September 1762*. St. Petersburg, St. Petersburg Imperial Academy of Science. Pp. 1-24 (in Russian).
- Rumovsky, S., 1771. *Observations of Venus on the Sun made in the Russian Empire in 1769 ...* St. Petersburg, St. Petersburg Imperial Academy of Science (in Russian).
- Russell, H.C., 1883. Observations of the transit of Venus, 1874, December 8-9, made at Stations in New South Wales. *Memoirs of the Royal Astronomical Society*, 47, 49-88.
- Russell, H.N., 1899. The atmosphere of Venus. *Astrophysical Journal*, 9, 284-299.
- Schaefer, B.E., 2001. The transit of Venus and the notorious black drop effect, *Journal for the History of Astronomy*, 32, 325-336.
- Schilling, G., 2011. *Atlas of Astronomical Discoveries*. Springer, New York.
- Schröter, H., 1792. Observations on the atmospheres of Venus and the Moon ... and the twilight occasioned by them. *Philosophical Transactions of the Royal Society*, 8, 322.
- Sharonov, V.V., 1952a. Determination of the horizontal diffraction in the atmosphere of Venus from the observations of Lomonosov's phenomenon. *Doklady USSR Academy of Sciences*, 82, 351-353 (in Russian).
- Sharonov, V.V., 1952b. Lomonosov's phenomenon and its importance for astronomy. *Astronomicheskij Zhurnal*, 26, 728-737 (in Russian).
- Sharonov, V.V., 1955. On the priority of M.V. Lomonosov in the discovery of the atmosphere of Venus. *Scientific Bulletin of Leningrad University*, 13, 12-15 (in Russian).
- Sharonov, V.V., 1958. *The Nature of Planets*. Moscow, Fizmatlit (in Russian). [English translation, Jerusalem: Israel Program for Scientific Translations, 1964.]
- Sharonov, V.V., 1960. Lomonosov as an organizer of the observations of the transit of Venus in 1761 in Russia and his discovery of the Venus atmosphere. In Karpeev, E.P., and Modzalevskij, A.I. (eds.). *Lomonosov: sbornik statei i materialov. Volume IV*. Moscow-Leningrad, USSR Academy of Sciences. Pp. 7-40 (in Russian).
- Sheehan, W., and Westfall, J., 2004. *The Transits of Venus*. Amherst, Prometheus Books.
- Shiltsev, V., 2012a. Mikhail Lomonosov and the dawn of Russian science. *Physics Today*, 65(2), 40-46.
- Shiltsev, V., 2012b. Lomonosov's Discovery of Venus' Atmosphere in 1761. English Translation of the Original Publication with Commentaries, *arXiv preprint arXiv:1206.3489*.
- Shiltsev, V., 2012c. Did Lomonosov see the Venusian atmosphere? *Physics Today*, 65 (11), 12.
- Shiltsev, V., Nesterenko I., and Rosenfeld, R., 2013. Replicating the discovery of Venus' atmosphere. *Physics Today*, 66(2), 64-65.
- Shirley, J.H., and Fairbridge, R.W. (eds.), 1997. *Encyclopedia of Planetary Sciences*. London, Chapman and Hall.
- Silberschlag, G., 1761. Historic and noteworthy news. *Magdeburgischen Privileg* [newspaper], XXIV. 13 June 1761 (in German).
- Smith, A., 1912. An early physical chemist - M.W. Lomonosoff. *Journal of the American Chemical Society*, 34, 109-119.
- Smith, W., Lukens, J., Rittenhouse, D., Sellers, J., and Maskeline, N., 1769. Account of the transit of Venus over the Sun's disk, as observed at Norriton, in the County of Philadelphia, and Province of Pennsylvania, June 3, 1769. *Philosophical Transactions of the Royal Society*, 59, 284-326.
- Stavinschi, M., 2012. Romanian astronomy and the 1874 transit of Venus. *Journal of Astronomical History and Heritage*, 15, 15-18.
- Sterken, C., and Duerbeck, H.W., 2004. The 1882 Belgian transit expeditions to Texas and Chile - a reappraisal. *Journal of Astronomical History and Heritage*, 7, 25-33.
- Strömer M., et al., 1761. Pa Observatorium i Upsala. *Kungliga Vetenskapsakademiens Handlingar*, 22, 144-152 (in Swedish).
- Struve, O.W., 1886. *Jahresbericht über die Thätigkeit der Kaiserlichen Nicolai-Hauptsternwarte*. St Petersburg, St Petersburg Imperial Academy of Science (in German).
- Struve, O., 1954. Lomonosov. *Sky and Telescope*, 13, 118-120.
- Tanga, P., Widemann, T., and Sicardy, B., 2011. The aureole of Venus: light refraction in the mesosphere during the solar transit of June 6, 2004. In *EPSC-DPS Joint Meeting. EPSC Abstracts*, 6, pp. 2.
- Tanga, P., Widemann, T., Sicardy, B., Pasachoff, J.M., Arnaud, J., Comolli, L., Rondi, A., Rondi, S., and Sütterlin, P., 2012. Sunlight refraction in the mesosphere of Venus during the transit on June 8th, 2004. *Icarus*, 218, 207-219.
- Tchenakal, V.L., 1961. M.V. Lomonosov and his astronomical works. *The Observatory*, 81, 183-189.
- Tebbutt, J., 1883. Observations of the transit of Venus, 1874, December 8-9, made at Windsor, N.S. Wales. *Memoirs of the Royal Astronomical Society*, 47, 89-92.
- Tobin, W., 2013. Transits of Venus and Mercury as muses. *Journal of Astronomical History and Heritage*, 16, 224-249.
- Tyulichev, D.V., 1988. *Publishing Activities of St. Petersburg Academy of Sciences and M.V. Lomonosov*. Leningrad, Nauka. Pp. 228-229 (in Russian).
- Vavilov, S., and Kravets, T. (eds.), 1950-1983. *Complete Works of M.V. Lomonosov, Eleven Volumes*. Moscow and Leningrad, USSR Academy of Sciences (in Russian). [Also available online from Russian

National Fundamental Electronic Library "Lomonosov" <http://feb-web.ru/feb/lomonos/default.asp>]

Wargentin, P.W., 1761-1762. Observations on the same transit; and on an eclipse of the Moon, May 8, 1761; and of the Sun, on the 3d of June 1761 ... *Philosophical Transactions of the Royal Society*, 52, 208-213.

Wulf, A., 2012. *Chasing Venus: The Race to Measure the Heavens*. New York, Alfred A. Knopf.

Vladimir Shiltsev is Director of the Accelerator Physics



Center at the Fermi National Accelerator Laboratory, Batavia, IL, USA. He is a Fellow of the American Physical Society, an amateur astronomer and a Lomonosov scholar, with articles on the Russian polymath in *Physics Today*, *Physics in Perspective*, *Science First Hands*, and other popular publications.

He is the President of the International Russian-speaking Academic Scientists Association and played a leading role in organizing Lomonosov's Tercentennial Readings in Washington, DC, in 2011 and Lomonosov's discovery of Venus' atmosphere replication experiment during the 2012 transit of Venus. The results of that experiment were published in *Solar System Research*, *Journal of the Royal Astronomical Society of Canada* and *Physics Today*.