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Transits of Venus: New Views of the Solar System and Galaxy
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Mikhail Lomonosov and the discovery of the atmosphere of Venus during the 1761 transit

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Abstract. The atmosphere of Venus was discovered for the first time by the Russian scientist Mikhail V. Lomonosov at the St Petersburg Observatory in 1761. Lomonosov detected the refraction of solar rays while observing the transit of the planet across the disk of the Sun. From these observations he correctly inferred that only the presence of refraction in a sufficiently thick atmosphere could explain the appearance of a light ('fire') ring around the night disk of Venus during the initial phase of transit, on the side opposite from the direction of motion. Lomonosov described this phenomenon, which carries his name, as the appearance 'of a hair-thin luminescence', which encircled a portion of the planet's disk that had not yet contacted the solar disk. He also observed a bulge set up at the edge of the Sun during the egress phase of the Venus transit. 'This bears witness to nothing less than the refraction of solar rays in the Venusian atmosphere', he wrote. This paper is based on the original Lomonosov publications and describes historical approaches to the study involving procedure, drawings, and implications.

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1. Introduction

On 8 June 2004 and on 6 June 2012 mankind has the chance to witness a historical celestial event when the silhouette of Venus crosses the face of the Sun. Obviously, a transit of Venus across the Sun's disc can occur only when the planet is at the inferior conjunction at one of the points in its orbit where the orbital plane crosses the plane of the ecliptic (along the line of nodes) in every June and December. However, because of the necessary orbital configurations and significant eccentricity of the Earth's orbit, such an astronomical oddity is comparatively rare, repeating in cycles whose intervals are 8 yr, 105.5 yr, 8 yr, and 121.5 yr. The last four occurred in 1761, 1769, 1874, and 1882. Thus, after 2012 our descendants will not have an opportunity to observe the next pair again from the Earth until December 2117.

The first observed transits have been of the great value because they allowed us to determine the solar parallax, and thereby the scale of the solar system, with an uncertainty of astronomical unit only a few million km. Although being incomparable with the today's AU accuracy (about 5 m), it was a great achievement in the 18th century. Additionally, during the transit of 1761 an atmosphere around Venus was discovered.

The first evidence of solar rays' refraction in the Venusian gas envelope was supported by the follow-up observations. It was found that contours of the visible disk are indeed considerably influenced by an atmosphere. Refraction shifts the position of the terminator by producing a penumbral zone, where one can observe a gradual decrease of illumination from the day hemisphere to the night hemisphere. One can also see the effect of the atmosphere in the elongation of the horns of the crescent when Venus is near inferior conjunction (Fig. 1). Because of refraction, the lighted arc of the limb appears to be greater than 180°, and each horn seems to be shifted towards the dark half of the limb (see, e.g., Sharonov 1953). In the extreme case, when the crescent is very thin, a complete

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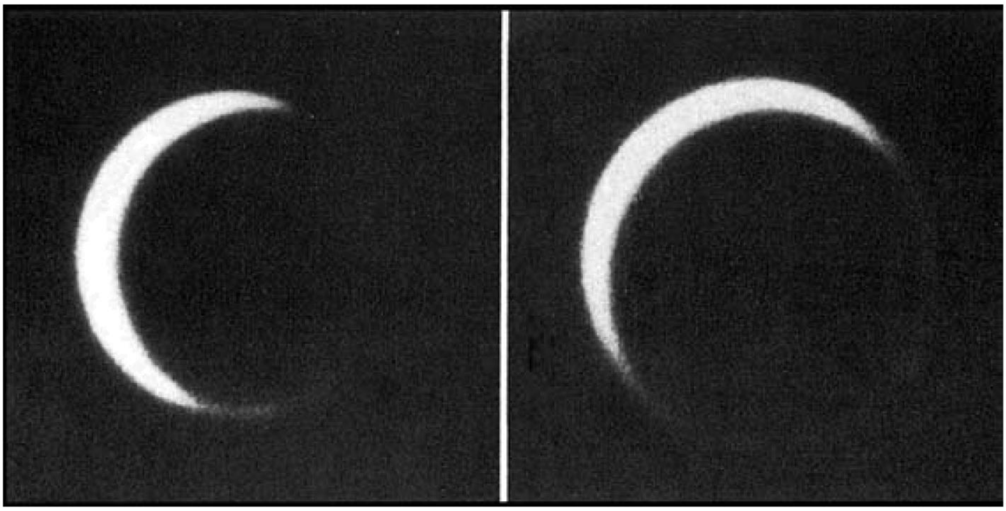

Figure 1. The crepuscular arc around Venus. The elongation of the horns is clearly visible, almost encompassing the disk.

ring of light is observed surrounding the planet. In addition to their intrinsic beauty, these phenomena have provided useful insights into some properties of the atmosphere, including the existence of high-altitude clouds.

The beginning of study of Venus' nature is attributed to Galileo Galilei, who first established the phases of the planet, analogous to the well-known phases of the Moon. Many valuable observations of planets were carried out medieval astronomers using rather primitive instruments, long before photographic plates were available. In particular, Johannes Kepler predicted that Venus would pass in front of the Sun on 6 December 1631, but it was not observed at that time from Europe. In England Jeremiah Horrocks (who observed jointly with his friend William Crabtree) had predicted the Venus transit on 4 December 1639 based on mathematical calculations that turned out even more accurate than those Kepler used, and this was the first recorded sighting of the event.

When addressing that historical time, it is worth noting that the beginning of successful astronomical observations and growing understanding of solar system configuration developed by Nicholas Copernicus naturally led some astronomers to surmise that neighboring planets might have atmospheres and that life might exist on them. In particular, such a possibility was seriously considered by Giordano Bruno who wrote: 'There are countless suns and countless earths all rotating around their suns in exactly the same way as the seven planets of our system. We see only the suns because they are the largest bodies and are luminous, but their planets remain invisible to us because they are smaller and non-luminous. The countless worlds in the universe are no worse and no less inhabited than our Earth' (Bruno 1584).

2. Historical highlights

That Venus does indeed have an atmosphere was first determined by the distinguished Russian scientist Academician Mikhail Vasil'evich Lomonosov at the St Petersburg Observatory. Lomonosov (Fig. 2) was born on 8 November 1711 in Cholmogori village near Arkhangelsk in the northern part of European Russia, and died on 4 April 1765 in St Petersburg. He graduated first from Slavonic-Greek-Latin Academy in Moscow and then from Marburg and Freiburg Universities in Germany. He was recognized in the different

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Figure 2. Mikhail V. Lomonosov. Painting after C.-A. Wortman (1757). Museum of M.V. Lomonosov, St Petersburg.

fields of natural sciences (first of all in physics and chemistry), as well as in philosophy, history and philology, and he was the founder of Moscow University, established in 1755.

Historically, the passage of Venus across the face of the Sun in 1761 drew the attention of numerous astronomers throughout the world. More than 40 different sites were selected and 112 astronomers observed the event. Beginning in 1760 many calculations of the visible path of Venus were undertaken. In Russia, the study was made by the physics professor France-Ulrich-Theodore Epinus, Director of the St Petersburg Observatory. He published in the October 1760 issue of the magazine 'Writings and Translations for Profit and Entertainment' his paper 'News on the Forthcoming Venus Transit Between the Sun and the Earth' accompanied by the three engraved drafts (Epinus 1760a).

Lomonosov, however, found the third of these drafts depicting the path of Venus across the solar disc insufficiently correct, and drew this fact to Epinus' attention. Because Epinus disagreed and argued for his being right in the 'Comments' that followed his first publication (Epinus 1760b), Lomonosov presented to the Academy Assembly on 18 December 1760 the special 'Note on the F. Epinus complaints that Lomonosov called in question his paper "News on the Forthcoming Venus Transit between the Sun and the Earth"' (Lomonosov 1760). The essence of the arguments of the critics was that, as Lomonosov stated, in his drawings Epinus:

1) did not take into account nearly 10° difference of the ecliptic position to the local horizon when observing the visible path of Venus across the Sun's disk in St Petersburg and also the respective corrections that should be introduced for Venus' entry/emergence in Siberia where expeditions were intended to be sent;

2) did not account for the declination of Venus' orbit relative to the ecliptic by $3°22'$ (a bit different from the contemporary value of $3°23'39''$) that influences the ephemerides evaluation and

3) did not refer to the original calculations of the Venus transit in different parts of the world, as it was shown in the special map earlier published in Paris.

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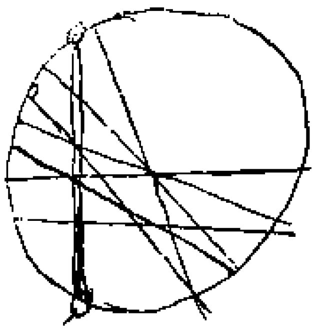

Figure 3. Lomonosov's drawing of different angles to the horizon under which an observer will see the actual Venus path for several sites in Siberia, accounting for local horizon and solar zenith distance and the proposed method to draw the path for every observer's position using a special device – the hodograph astrolabe.

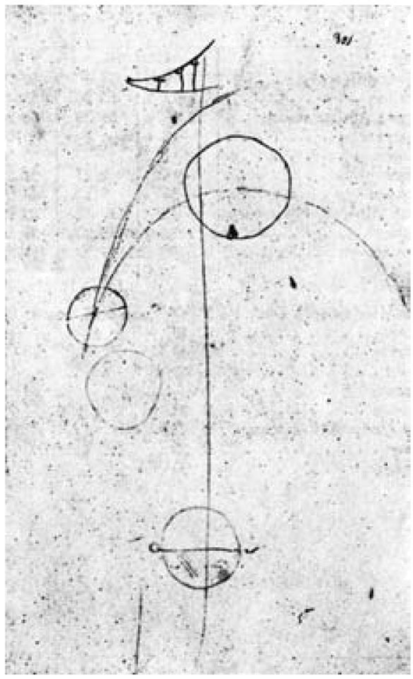

Figure 4. Lomonosov's drawing of an enhanced curvature of the Venus passage to an observer caused by changing of both ecliptic inclination and the path of Venus relative to the local horizon.

3. Observations and results

The discussion encouraged Mikhail Lomonosov to pay more attention to the event. During a few months of early 1761 he wrote a paper dealing with calculations of the Venus transit accompanied by a note with tables. The title of the paper was 'Venus Path Along the Solar Plane as It will be Seen to Observers in Different Parts of the World on May 26, 1761 According to the Calculations of Russian Academy of Science Adviser and Swedish Royal Academy Member' (Lomonosov 1761a). Eliminating the Epinus' errors and using the (Manfredi 1750) astronomical tables containing ephemerides of celestial bodies from 1751 to 1762, Lomonosov found the times when the Venus entry to the Sun and emergence at the St Petersburg site would occur. He thus determined that the total time of the event was to be $6^{\mathrm{h}}33^{\mathrm{m}}$ corresponding to angular distance on the Earth's surface $98^{\circ}\!.25$, the Venus path having a small curvature slightly pronounced to

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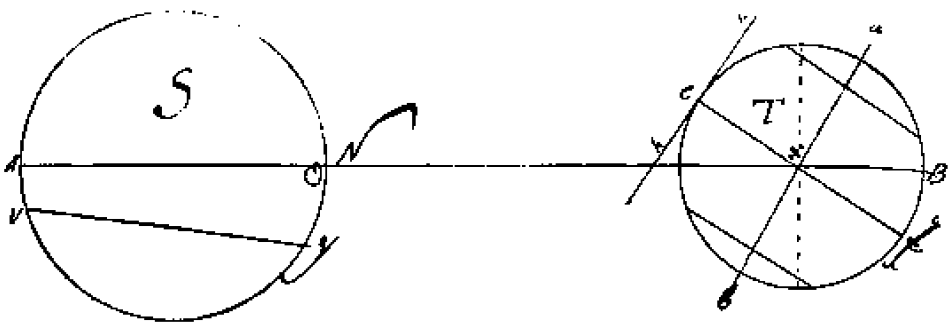

Figure 5. Lomonosov's drawings of Venus' transit across the Sun's disk. S is the Sun and T is the Earth, ANB – ecliptic running along the Sun's and Earth's centers, VY – Venus path as it is seen from the center of the Earth, ab – the Earth's axis, ef – equator, x – site on the Earth's surface at the equator pointing to the center and orthogonal to AB.

the observer. This is because both ecliptic inclination and the Venus path change relative to the horizon in the course of its passage depending on the local positions on the Earth's surface. The original Lomonosov drawings of the event are shown in Figs 3 and 4.

In his evaluation Lomonosov specially emphasized the importance of accurate position and time of the planet's entry to the solar disk in order that the observers would not miss the very beginning of the first contact. This is why he calculated the time of Venus-Sun first contact and emergence for several sites in Siberia accounting for the local horizon and solar zenith distance, in other words, different angles to the horizon at which an observer will see the actual Venus path.

The results of these calculations are shown in Fig. 5. He suggested a special device to draw the Venus path wherever the observer's position is (see Fig. 6), which he called the hodograph astrolabe, applicable also for observing solar eclipses (Lomonosov 1761a).

Based on this preparatory work, astronomical observations of Venus transit at the St Petersburg Observatory were carried out by the very skilled and experienced astronomers Andrey D. Krasilnikov and Nikolay G. Kurganov using a 6-feet-long focus telescope. The contact of the rear side of Venus' disk occurred at $4^h26^m39^s$, the exit of its front side occurred at $10^h19^m04^s$, and exit of its rear side (Venus left the Sun) at $10^h37^m00^s$. From these measurements the diameter of the Sun was deduced to be as large as $0°31'36''$, and the diameter of Venus as large as $01'02''$. The total time of the planet's conjunction with the Sun was found to be $7^h43^m05^s$, and inclination angle of its path to the eastward longitude circle was $81°29'00''$ (Lomonosov 1761a). The results of these observations gave rise to the solar parallax value $8\overset{''}{.}49$, not too different from the contemporary value $8\overset{''}{.}794148$.

In turn, Lomonosov himself focused on the observations of physical phenomena that accompanied the Venus transit. For this purpose he used a sort of spyglass – the 4.5-feet two-lenses tube covered with a smoky glass. The results of these remarkable observations he described in his paper 'The Appearance of Venus on Sun as It was Observed at the St Petersburg Emperor's Academy of Sciences on May 26, 1761' (Lomonosov 1761b; Lomonosov 1761c). We shall quote here a few paragraphs from this paper referring also the drawings in Fig. 7:

> 'Following the ephemerides I had, I waited for about forty minutes until the solar edge in the place of Venus ingress, which was clearly seen before (see 'B' in Fig. 7.1), became unexpectedly vague and obscured. I thought initially that my tired eye caused an obscuration, but when looking again in a few seconds I found a black indentation from the coming Venus, which replaced the former vague spot. I continued to look attentively how the trailing side of the planet approaches the

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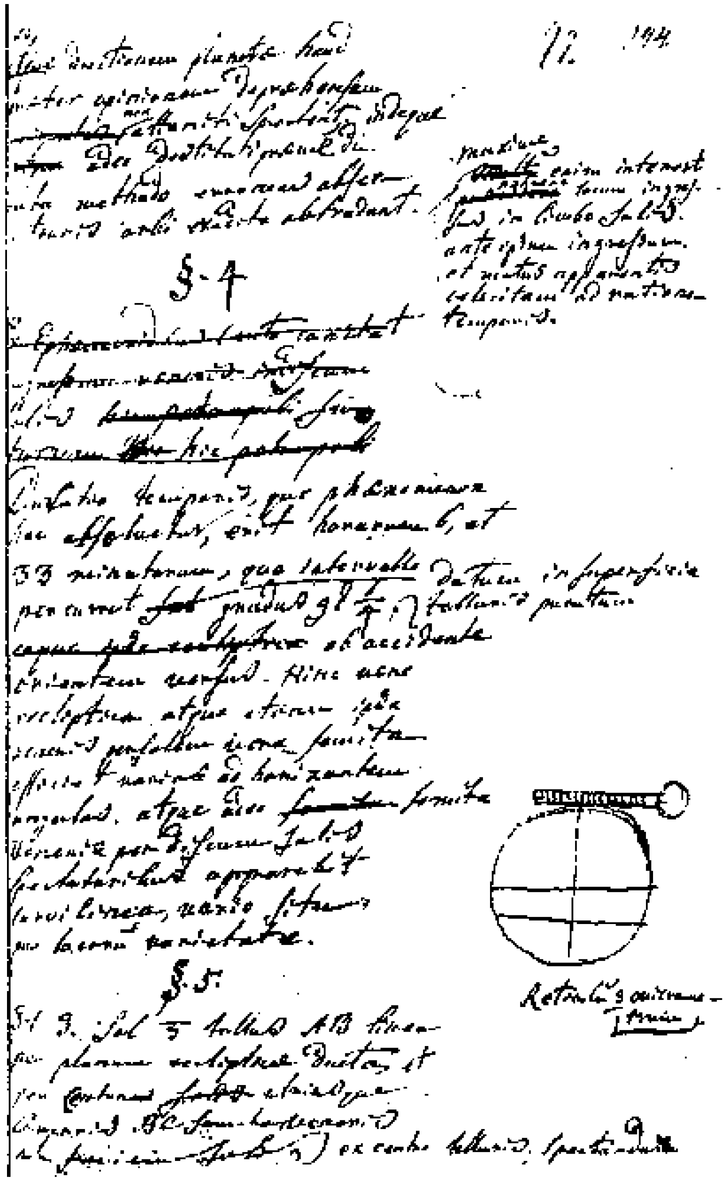

Figure 6. A sample page from the manuscript of the Lomonosov's paper 'Venus Path Along the Solar Plane...'. In the drawing a special device called hodograph astrolabe is shown.

Sun; suddenly, a hair-thin bright radiance (luminescence) between Venus' trailed side and solar edge appeared that lasted only less than a second.

Before the Venus ingress, when its front side approached the solar edge at about one tenth of the planet's diameter, a bulge set up (see 'A' in Fig. 7.1) which progressively became more pronounced as Venus came to leave the Sun (see Fig. 7.3 and 7.4, where LS is the solar edge and mm is a bulging Sun). Soon after that the bulge disappeared and instead, Venus appeared with no edge (see nn in Fig. 7.5). Similar to the ingress phase, the last touch of the planet's trailing side at the emergence was also accompanied by a small break and solar edge obscuration.

Because colors caused by the light rays refraction appeared stronger as larger was a Venus offset from the tube center X (see Fig. 7.2), I permanently maintained the tube in the position with Venus in the tube center. It provided a clear image of the planet with no colors at its edges.

Based on these observations I conclude that the planet Venus is surrounded by a distinguished air atmosphere similar (or even possibly larger) than that is poured

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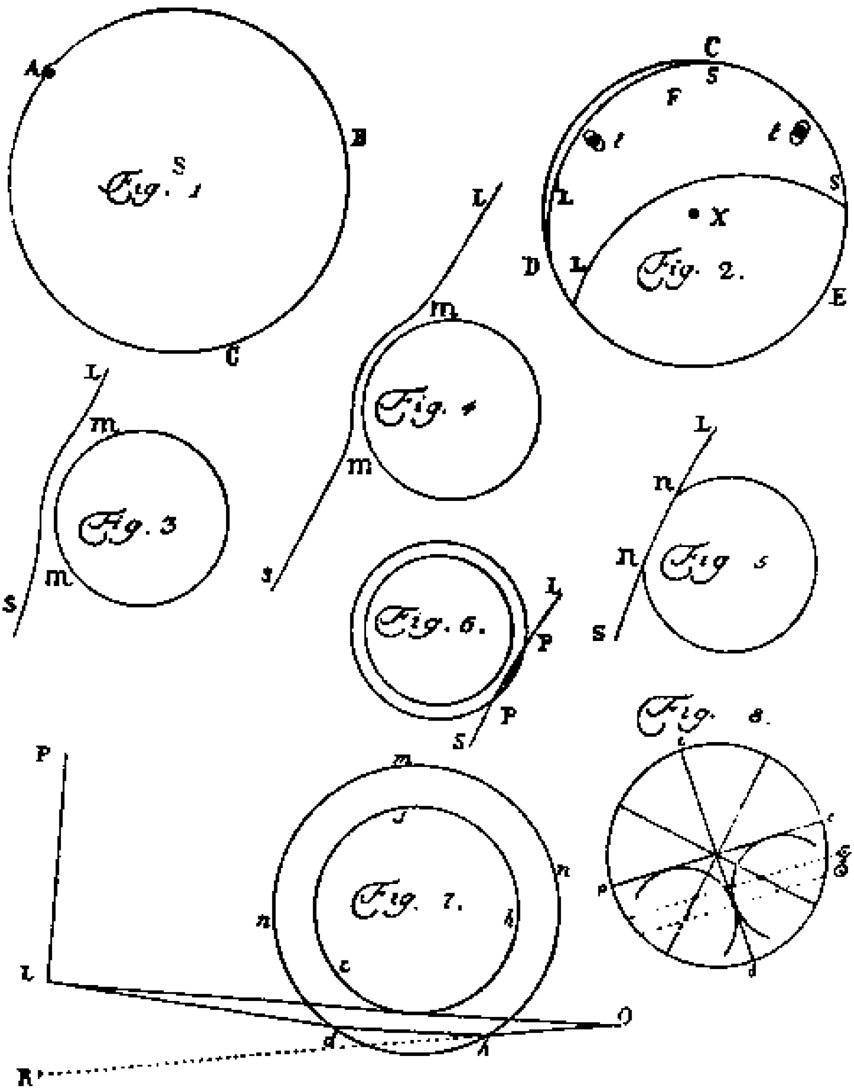

Figure 7. Lomonosov's drawings of the sequence of physical events accompanied the Venus transit across the Sun's disc at the entry and exit phases: 1 – losing clearness at the solar disc edge just before Venus entered the solar surface 'B' and bulge set up 'A' in the place of Venus leaving the Sun; 2 – colors caused by the light rays' refraction appeared offset from the tube center X; 3 and 4 – a bulge progressively becomes as more pronounced as Venus leaves the Sun, LS is the solar edge and mm is a bulging Sun; 5 – the planet appeared with no edge soon after the bulge disappeared (see nn); 7 – the bulge formed close to the solar disc edge at the time of Venus' emergence for which the refraction of solar rays in the Venus atmosphere should be responsible. Here L in the line PL is the end of the Solar diameter (solar disc edge), cjh is the Venus solid body, mnn is its atmosphere, LO is the tangent to the solid Venus body along which an observer O would see the solar disc edge at the point L in the absence of atmosphere, LdhO is the path along which the solar light propagate due to atmospheric refraction at dh, and OR is offset of solar edge L as it is visible to an observer.

over our Earth. This finding is supported by the following arguments. Firstly, losing clearness at the solar disc edge ('B' in Fig. 7.1) just before Venus entered the solar surface means that the edge was obscured by the Venus atmosphere. Secondly, for the bulge formed close to the solar disc edge at the time of Venus emergence, the refraction of solar rays in the Venus atmosphere should be responsible. Indeed, let us address the Fig. 7.7 where L in the line PL denotes the end of the Sun diameter (solar disc edge), cjh is the Venus solid body, and mnn is its atmosphere. In the

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absence of the atmosphere an observer O would see the solar disc edge at the point L along the line LO that is the tangent to the solid Venus. In the case of the atmosphere, however, the solar light will propagate along the curve LdhO due to refraction at the path dh. It is known from optics that an eye see along the incident line; therefore, the solar edge at L turns out shifted at the point R along the virtual line OR. An excess LR compared to the real solar radius explains the bulge formation before the front side of Venus at the time of its emergence from the Sun.'

In the second part of his paper Lomonosov discusses philosophical aspects of this important discovery in the context of how astronomy has progressed since ancient times and how it impacted on both the world outlook and practical needs such as navigation. He addresses many problems involving the possibility of numerous habitable worlds in the Universe (in parallel to Giordano Bruno's paradigm cited above) and correlation between nature and religion that he considers as two Main Books given to mankind by God. The discussion is even accompanied by two short poems written by himself in support of the heliocentric system of Nicholas Copernicus which was still obscured by the church.

4. Discussion

Lomonosov detected the refraction of solar rays while observing the Venus transit across the disk of the Sun during both entry and emergence phases in 1761. Only the presence of refraction in a sufficiently thick gas envelope could explain the appearance of light ('fire') ring around the night disk of Venus at the entry phase and a bulge formation close to the solar disc edge during the Venus emergence. It should be noted, however, that Lomonosov's description of the observed phenomenon during the initial phase of transit, on the side opposite from the direction of motion, is not fully accurate: it seemed to him as 'a hair-thin bright radiance (luminescence) between Venus' back side and solar edge'. In reality, it was a bright thin rim which encircled a portion of the planet's disk that had not yet contacted the solar disk and thus separated the Venus limb from the sky's background. Interestingly enough, some observers of the following Venus transits in 1874 and 1882 similarly reported that a 'fire ring' seemed projected on the planetary disc as well. Nonetheless, Lomonosov's interpretation of losing clearness at the solar disc edge, just before Venus entered the solar surface, in terms of its atmosphere occurrence was correct, and even more conclusive was his thorough explanation of the bulge appearance when the planet left the Sun.

In general, Lomonosov properly described the physical mechanism underlying his observations and came to the right conclusion that Venus possesses an atmosphere which could be comparable to, or even more dense than that of the Earth. It fully paralleled the basics of the refraction theory he earlier studied with implications for accuracy of navigation at sea. According to Lomonosov (1759), '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'. Only in the middle of 1960s did it become clear that his assumption that Venus' atmosphere can be 'even more dense than that of the Earth' was far-sighted, because Venus' atmosphere turned out nearly two orders of magnitude thicker than the terrestrial standard indeed (see, e.g., Marov & Grinspoon 1998).

The paper of Lomonosov, where his observations and discovery of Venus' atmosphere were described, was submitted for publication on 4 July 1761 and 200 copies were published in Russian on 17 July 1761 (Lomonosov 1761b). In parallel, Lomonosov prepared a German translation of the paper which appeared in August 1761 (Lomonosov 1761c) and hence, became more available to the world scientific community. However, when

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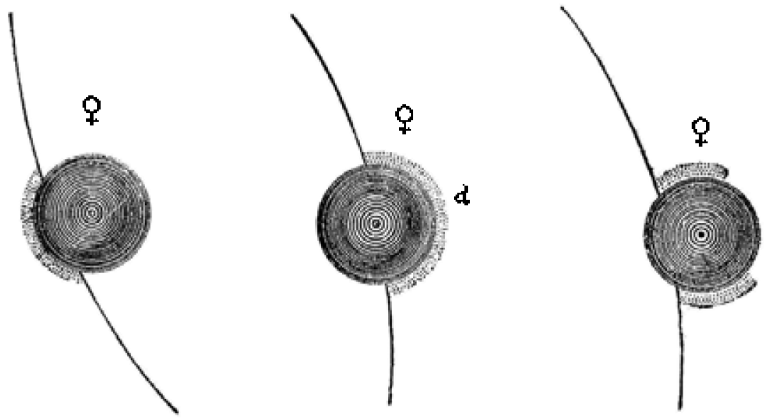

Figure 8. Bergman's drawings in support of the finding of Venus' atmosphere. The three sequence from the light illumination of Venus' trailed side before it fully crossed the solar disk, to the second and third ones showing the more pronounced bright light at the front side of Venus at the emergence, which eventually attenuated and ultimately only horns were left (Bergman 1762).

approximately 30 years later the German astronomer Johan Hieronymus Schroeter and the English astronomer Frederick William Herschel discovered the above-mentioned crepuscular phenomena on Venus and came to the correct conclusion that they result from the scattering of solar rays in the upper portion of the planet's atmosphere, there were attempts to ascribe to them the finding of Venus' atmosphere and thus to lapse into silence on Lomonosov's priority. The history of the discovery, including the discussion between Schroeter and Herschel on some hot points, and later comments of French astronomer Dominique Francois Arago in support of the Venus atmosphere existence with tribute to the priority of the Lomonosov's discovery, can be found elsewhere (Perevozshikov 1865).

It is worth mentioning that Lomonosov himself was aware that it was not he alone who studied physical phenomena which accompanied the Venus transit. He wrote, 'The great atmosphere that we found around Venus was also noticed by other observers in Europe'. Among them, the most advanced observations were made in Uppsala by Tobern Olof Bergman who reported the results at the meeting of Royal Society in London on 19 November 1761. He argued for the finding of Venus' atmosphere based on three drawings (see Fig. 8). One may emphasize, however, that this and other observations and their analysis were much less detailed compared to what was made by Lomonosov. Also, these results were published later and in no way cast doubt on Lomonosov's priority.

5. Summary

The discovery of Venus' atmosphere was a great astronomical achievement in the 18th century. The Russian scientist Mikhail Lomonosov was the first who found it from the study of the solar rays' refraction patterns while observing the Venus transit across the solar disk in 1761. He argued correctly that only refraction in a sufficiently thick gas envelope could explain the appearance of a light ('fire') ring around the night disk of Venus at the entry phase and a bulge formation close to the solar disc edge during the Venus emergence. The Venus atmosphere discovery, in addition to astrometric measurements, clearly manifested the great importance of transit phenomena for astronomical science, with the basics of this technique being now readdressed to the study of extrasolar planets.

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Discussion

Suzanne Débarbat: Is the Lomonosov observatory on the top of the Academy where the Lomonosov museum is in St Petersburg? Or was it in another place? From where did he make his observations?

Mikhail Marov: No. The original St Petersburg observatory was at the top of the Academy building indeed (Pulkovo observatory was set up much later, in 1839), while the Lomonosov museum is just a branch of the Academy Institute of Natural History located in one of two wings of the Academy building.

Ed Budding: Did he measure the scale of the enhancement of the disc – the small bump which you mentioned – in relation to the size of the disc of Venus?

Mikhail Marov: No – just what I describe. This is the bulge; it's the solar disc ... when Venus was just leaving the sun. It is because of the refraction that to you it looks like an enhancement, like it's a bulge in the solar disc.

Ed Budding: Yes, we are agreed about that. What I ask is: what is the number which you put on the size of this bulge?

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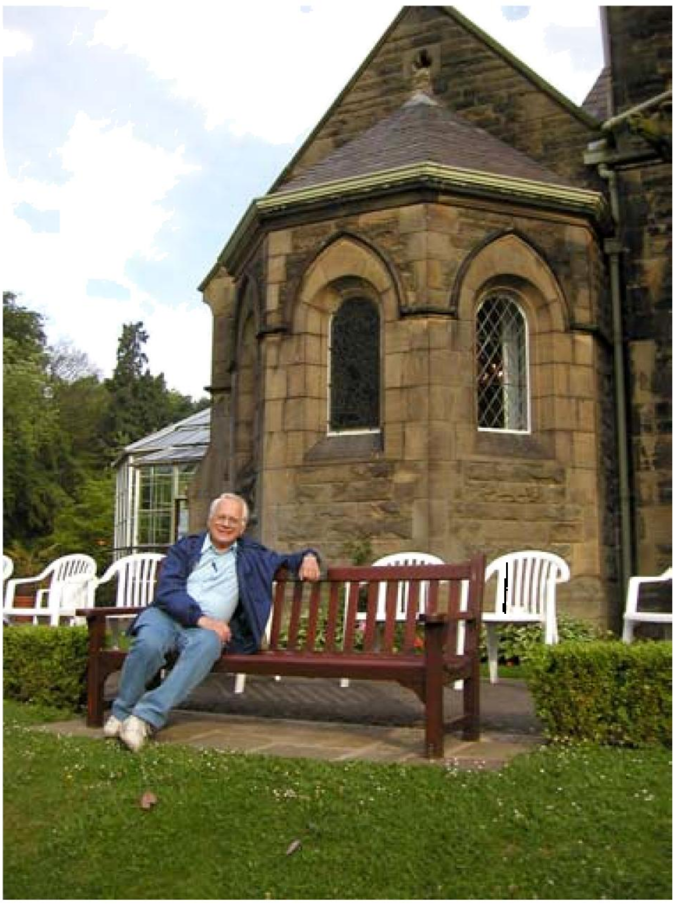
Mikhail Marov: Well, I can't answer your question quantitatively, but I can tell you that it was sufficient to be discernable when observing with the eye. I tried just to do the same yesterday! It was a rare opportunity, but because of bad luck with the weather conditions it turned out impossible essentially – I saw nothing.

Wayne Orchiston: An interesting paper: Do we have any of the original records, the observations and archival material of his work, or is the only thing that survived the actual publication of his results?

Mikhail Marov: Yes, we have a very good archive of Lomonosov. It is very well preserved, and this is just in some picture book. I had only limited access to these archives, so I mostly used just what was published later. The most comprehensive from the archives are eight volumes of work written by Lomonosov that were published by the Soviet Academy of Science in 1955; this is everything: this is science, this is poetry, this is history. These volumes were quite accurately made by the people who went through all the available manuscripts. The manuscripts themselves are accessible usually only to specialists who study history.



Mikhail Marov at Alston Hall

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