DOI: 10.6093/978-88-6887-281-6

From the Earth to the Sun: The Quest for the Astronomical Unit by Means of the 1761 and 1769 Venus Transits

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Abstract: In the mid-eighteenth century, one of the most urgent astronomical problems was to determine the exact value of the Earth-Sun distance (the so-called Astronomical Unit, AU), necessary to establish the real dimension of the entire solar system. The most promising methods for measuring the AU, due to Edmond Halley (1656-1742) and Joseph-Nicolas Delisle (1688-1768), were both taking advantage of a rare phenomenon: Venus’ transit over the Sun, expected to occur in 1761 and 1769. According to those methods, observers – spread all over the two Earth hemispheres – taking simultaneous and accurate measurements of the transit would have enabled derivation of the solar parallax and hence of the AU (with an uncertainty of less than 1%, at least in Halley’s intent). Thus, in a world torn apart by the Seven Years War (1756-1763) and the subsequent struggles for colonial hegemony, more than 250 astronomers and scholars from different nations, animated by a common purpose in the spirit of Enlightenment, gave life to an incredible joint venture, never attempted before, which is considered the first international scientific collaboration. Among them, was the Italian scientist Giovanni Poleni (1683-1761), who observed the 1761 transit from Padua. Padua looks then the right location in which the story of the two Venus transits can be told. A story that was not only an incredible astronomical enterprise but also a masterful example of how science had and has still today the power to overcome national boundaries and hostilities.

Keywords: Venus’ transits, Astronomical Unit, Solar parallax

1. Incipit

> Quippe mihi non multo minus admirandae videntur occasiones, quibus homines in cognitionem rerum coelestium deveniunt, quam ipsa Natura rerum coelestium [The roads by which men arrive at their insights into celestial matters seem to me almost as worthy of wonder as those matters in themselves] (Kepler 1609, Argumenta singolorum capitum – Caput XLV).

Those words were written by Johannes Kepler (1571-1630), in his *Astronomia Nova*, a masterpiece published in 1609, and which constitutes a milestone in the history of astronomy.

And this statement is well suited to the astronomical story that will be narrated in the following pages, and which tells of the realization of a colossal scientific venture – the one relating to the two transits of Venus of 1761 and 1769 – rather than focusing on its astronomical results.

2. Where it all started

This story began in 1677, when Edmond Halley (1656-1742) observed the transit of Mercury across the Sun from the island of Saint Helena (Halley 1679).

At the end of the seventeenth century, the transit of Mercury was considered one of the means to determine the Earth-Sun distance (today also known as Astronomical Unit, AU), which constituted the unit of measurement for planetary distances and, therefore, also of the dimensions of the entire solar system. The phenomenon occurred from 12 to 14 times every century, thus providing multiple opportunities to make observations. However, Halley was convinced that, despite the high frequency of

Mercury transits, they could hardly be used to derive the solar parallax (and, hence, the AU), and, in a short essay published in 1716, he stated that Mercury was too small and too close to the Sun to measure the little displacement observed from different places.

> About 40 years ago, on the Island of Saint Helena, I was engaged in observing the stars around the South Pole; it happened to me to observe, with the utmost care, the passage of Mercury across the Sun's disk, and contrary to expectation, I very accurately obtained, with a good 24-foot telescope, the very moment in which Mercury, entering the Sun's limb, seemed to touch it internally, as also that of his egress, forming an angle of internal contact. Hence, I ascertained the precise interval of time at which [the whole body of] Mercury had appeared entirely within the Sun's disk, even without the error of one single second time; for, the thread of solar light, intercepted between the dark edge of the planet and the bright limb of the Sun, though exceedingly slender, affected my sight; and in the twinkling of an eye, both the indenture made on the Sun's limb by Mercury entering into it vanished, and that made by his egress appeared. But on observing this, I immediately understood that the Sun's parallax might be correctly determined by such observations, if only Mercury, being nearer the Earth, had a greater parallax [when seen] from the Sun; for this difference of parallaxes is so small, as to be always less than the Sun's parallax, which we are looking for; consequently, Mercury, though frequently seen on the Sun, will scarcely be fit for the present purpose (Halley 1716, pp. 456-457).

However, there was another planet that could prove much more useful: Venus. The planet could be the right *tool* to derive the solar parallax, but there was a drawback: unfortunately, the transit of Venus – a phenomenon predicted for the first time by Kepler (Kepler 1630) – is an extremely rare event, since it occurs every 129.5 and 113.5 years, in pairs of transits separated by 8 years.

Halley knew that he would not live long enough to observe this phenomenon, but others after him would have this precious opportunity, since in 1761 and again in 1769, the planet would have been moving across the solar disk. It was thus of fundamental importance that several astronomers located in different places (in both hemispheres) would not miss that astronomical event.

3. Preparation of transits' observations

In 1760, the French scholar Joseph-Nicolas Delisle (1688-1768) accepted Halley's astronomical *call to arms* and published his *Mappemonde* (Delisle 1760a), that is, a geographical map of the entire terrestrial globe, indicating the best locations from which to make observations.

In fact, the transit of Venus is not visible everywhere: in some areas only the ingress of Venus on the solar disk can be observed, in others only the egress phase can be seen, and only in certain areas (not necessarily corresponding to mainland locations) is possible to observe the phenomenon for its entire duration. For example, in 1761, much of Europe would have witnessed only the final part of the transit, as did the whole of Africa. In observatories located in Asia, instead, it would have been possible to follow Venus throughout its whole journey across the solar disk.

Since a similar opportunity would not arise again for more than a century, it was thus essential that the scientific community take advantage of this extraordinary event. Therefore, Delisle sent his *Mappemonde* to the main European Academies of Sciences and the most famous astronomers of the time, inciting his colleagues to join forces and encouraging the widest diffusion and maximum participation, in order to observe the imminent astronomical event.

Halley and Delisle each proposed their own method of observation: that of Halley (Halley 1716) involved the determination of the observatory's latitude and the measurement of the entire duration of the transit. Delisle's method (Delisle 1760b, pp. 469-471), on the other hand, only required the exact measurement of one of the four moments of contact between the edge of Venus and the Sun's disk (thus broadening the range of possible locations from which to make observations), but it had the drawback of requiring not only the latitude, but also the longitude of the observatory – at the time, far more complex to determine –. Two different methods, then, but with one aspect in common: they both required multiple simultaneous observations, from different locations as distant as possible.

In fact, the transit would have lasted several hours, depending on how close to the solar disk centre Venus would have passed. Moreover, the time spent by the planet to cross over the Sun surface would have depended on the location of the observer; the difference in the crossing time coupled with the distance of the observers would have been the *key* for the calculation of the solar parallax – which, at least in Halley's intent, could have been determined "to within its five hundredth part" (Halley 1716, p. 460).

It was, thus, of paramount importance that astronomers had been well prepared for the event, since several observers should have been sent to different places in order to combine their transit measurements. No observation alone, however precise and accurate, would have been of any use: the scientific community necessarily had to collaborate, becoming *e pluribus unum* (Lovisetti 2022).

4. How to find the Earth-Sun distance?

But how was it possible to exploit the transit of Venus to obtain the Earth-Sun distance? To answer this question, we must go back to 1619, the year in which Kepler published his *Harmonices Mundi*.

There, Kepler presented what is now known as the third law of the motion of the planets, which provided the relationship between the square of the period of the planets and the cube of their average distance from the Sun: "It is absolutely certain and exact that the proportion between the periodic times of any two planets is precisely the sesquialternate proportion [*i.e.*, the ratio of 3:2] of their mean distances" (Kepler 1619, p. 189). In this law, the distances from the Sun were expressed by means of the Earth-Sun distance r_E; Kepler had thus obtained the distances of the planets as a function of the AU, but this value was the subject of strong discussions and disagreements.

In 1620, in the *Epitome*, Kepler estimated it to be equal to 3,469 r_E, that is about 21 million km:

> Even if the reasons of Copernicus do not extend to determining by observation the altitude of the sphere of the fixed stars – so that the altitude seems to be like infinity – for in comparison with this distance, the whole interval between the Sun and the Earth, which according to the judgment of the Ancients embraces 1,200 but by our true accounts comprises 3,469 semidiameters of the globe of the Earth, is imperceptible; nevertheless reason, making a stand upon the traces found, discloses a footpath for arriving even at this ratio (Kepler 1620, p. 490).

After Kepler, other scholars also attempted to determine the AU. In 1639, the English amateur astronomer Jeremiah Horrocks (1618-1641) realised that a transit of Venus was expected in December of the same year. The event had not been predicted by Kepler, who had foreseen the transit of 1631 (of which, however, no observations were ever reported) but not that of 1639, due to wrong calculations. Therefore, together with his friend, William Crabtree (1610-1640), Horrocks was the first to observe a Venus transit (and apparently the only one to observe it, in 1639), obtaining "the parallax of the Sun being nearly 0'14" at a distance, in round numbers, of 15,000 of the Earth's semi-diameters" (Hevelius 1662, p. 142), that is about 96 million km. Regrettably, Horrocks died prematurely in 1641, and his work was published only posthumously, in 1662, by Johannes Hevelius (1611-1687).

In 1659, in *Systema Saturnium*, the Dutch mathematician and astronomer Christiaan Huygens (1629-1695) obtained the value 12,543 d_E, about 160 million km (Huygens 1659, p. 80). Unfortunately for him, his reasoning was based on a purely speculative and unproven initial assumption, namely that: "in order that the harmony of the entire system can be conserved as much as possible, […] it is most reasonable to admit that, since the Earth is placed between Mars and Venus with respect to the distances, it also occupies an intermediate place with respect to size" (Huygens 1659, p. 80). Therefore, his method was considered scientifically unacceptable.

Instead, a scientifically acceptable procedure was used by the Italian scholar Giovanni Domenico Cassini (1625-1712), in 1684. Exploiting the opposition of Mars of 1672, he obtained the value (21,600$\pm$2,700) r_E (Cassini 1684, p. 47), about 139$\pm$17 million km. However, it was impossible not to notice that Cassini's estimate was affected by an uncertainty of about 12%: it was therefore clear that far better could (and had to) be done, and the two transits of Venus of 1761 and 1769 would have offered astronomers the perfect opportunities for this purpose.

In fact, as we have previously said, the phenomenon made it possible to determine the solar parallax, that is the angle π subtended by the Earth radius, when the latter is ideally seen from the Sun. If we consider the right-angled triangle with the Earth radius r_E and the Earth-Sun distance AU as its catheti, thanks to the simple trigonometric formula $\tan \pi = r_E/AU$, the parallax is linked to the AU. And since the Earth radius had been substantially known since the time of Eratosthenes of Cyrene (c.276-c.195 BC), the calculation of the Earth-Sun distance was, at least in theory, immediate.

Furthermore, when it moves across the solar disk along one of its chords, Venus appears as a small black spot. Therefore, the planet could be used as a precise and common reference point by different observers, who could put their observations together, thus determining the value of the solar parallax, through triangulation. Apparently, something very simple to say but actually not so easy to realise.

5. The first international scientific collaboration

And so it was that on June 6, 1761, and June 3-4, 1769, more than 250 astronomers coming from different countries and spread across more than 150 different stations, joined forces to carry out what is considered the first international scientific collaboration. This fact, already extraordinary in itself, is even more incredible if we consider that, in that period, the main European powers were at war with each other: in fact, the transit of 1761 occurred in the middle of the Seven Years' War, a conflict that tore the whole Europe from 1756 to 1763, and whose aftermath dragged on for decades, due to the subsequent struggles for colonial hegemony.

Despite the dangers and the objective difficulties, the main Academies of Sciences organized numerous expeditions, often grouping scholars from enemy countries and sharing astronomical equipment. In this enlightened climate of trust in the neutrality and supremacy of science, many brave scientists, first and foremost for the sake of science (but also in search of personal fame and glory), left for the most remote and inaccessible locations of the then known world, such as the icy Siberia, the distant island of Newfoundland, the exotic India, and the mysterious and still almost unexplored *Terra Australis*. In their travels, which in many cases lasted months, if not even years – as in the case of the Frenchman Guillaume Le Gentil (1725-1792), who stayed away from home for 11 years, 6 months and 13 days (Le Gentil 1779, p. 77) – amidst a multitude of vicissitudes and unpredictable events, those astronomers (today often unknown and forgotten) dedicated themselves to exhausting and repeated observations, in order to obtain extremely accurate data.

At the crucial moment, after so much waiting and so much effort, only a few of them were lucky enough to complete their missions: in fact, many of them observed a desolately cloudy sky; one – the American astronomer David Rittenhouse (1732-1796) – even passed out from fatigue and emotion; some did not even reach their destination; and others, unfortunately, never returned home. Such a fate fell to the Frenchman Jean-Baptiste Chappe d'Auteroche (1722-1769) and the Spaniard Salvador de Medina (d.1769), both perished during their joint expedition to California, in 1769; but also to Charles Green (1734-1771), the young and unfortunate British astronomer who sailed aboard *HMS Endeavour*, the ship of James Cook (1728-1779), during his first voyage in the Pacific Ocean, aimed at observing the 1769 transit.

6. Cloudy sky above Padua

Among those who took part in that colossal undertaking, was the Italian scholar Giovanni Poleni (1683-1761), who decided to observe the 1761 transit (the only one visible in Italy, and limited to the egress phase), from the city of Padua.

Poleni was already familiar with planetary transits, having observed the transit of Mercury in 1723 (Poleni 1724), but, at the same time, he was perfectly aware of the fact that many other astronomers – much more experienced than him and also equipped with better instruments than his own – would try their hand at the task. In any case, he was eager to carry out his own observations.

> Although it was known to me that many distinguished men had been moved to observe the same phenomenon, well equipped with instruments for that purpose, and well trained in astronomical observations, I thought that it would not be entirely useless if I myself should try something, not so much in the hope of succeed, especially in that adverse cloudy constitution of heaven, rather by the will to experience it (Poleni 1761, § 1).

Therefore, assisted by a group of learned friends and experts (including his son Francesco), he prepared with great care for the imminent astronomical event. For his observation, lacking better devices, he chose an instrument defined as “similar to a Hevelian heliometer” (Poleni 1761, § 3), that is, a helioscope (Hell 1761, f. 10v), like the one used by Horrocks 122 years before. Poleni thus placed in a dark room a refracting telescope, not equipped with a micrometer, which projected the image of the transit onto a sheet of paper, on which the astronomer had previously traced a circle (corresponding to the image of the Sun), to more easily record the position of Venus during the transit. A “crude method” (Hell 1761, f. 10v), but still functional:

> Previously, I took care to trace on the paper […] a drawing with a circle exactly equal to the image of the Sun; first of all, so that […] it could constantly converge with the environment of the image; then, in order to be able to mark more easily the centre of Venus in any position, and for this purpose a thin strip was prepared, divided in two, […] as wide as the [possible] diameter of the image of Venus (Poleni 1761, § 4).

Unfortunately, the observation of Poleni was not true glory, but not for faults attributable to the astronomer. In fact, on the morning of June 6, the sky over Padua was covered in clouds, with the transit visible only fleetingly.

> Before the sunrise […], we were ready to observe. […] the sky was densely covered with clouds […]. Then the clouds […] gradually thinned out […]. The image of the Sun appeared, however faint, and not sufficiently bright. Having seen the long-desired spectacle of Venus in the solar disk, we hastened, that […] we might collect some data […]. But […], the sky was covered with constant clouds on all sides, with no hope to observe the egress (Poleni 1761, §§ 6-8).

In addition to personal disappointment, Poleni did not even have the consolation of being able to know the value of the Earth-Sun distance obtained after the first transit, since he died on November 15, 1761, when calculations were still far from being completed.

7. The results of the colossal enterprise

In fact, after each transit, astronomers exchanged pages and pages of data, devoting months to make calculations. But despite the titanic efforts made, the first transit proved to be a complete failure, because the range of possible values found for the Earth-Sun distance after 1761 was too wide, resulting comprised between 123.9 million km and 158.8 million km (8.28”$< \pi <$10.60”).

Things went far better after 1769, when the observations led to a value of 152.8-154.6 million km ($\pi =$ 8.50”-8.60”), according to the calculations made by the French astronomer Joseph Jérôme Lalande (1732-1807) (Lalande 1772, p. 42; Lalande 1774, p. 798), and – after numerous controversies on the authenticity of the results obtained – to 150.8±0.2 million km ($\pi =$ 8.70”±0.01”), according to the Hungarian scholar Maximilian Hell (1720-1792) (Hell 1771). However, despite the great step forward, the precision obtained was not entirely satisfactory, since the uncertainty found by comparing all the data collected (that is, 8.43”$< \pi <$ 8.84”) was greater than that requested by Halley in 1716. In fact, to obtain the precision desired by the English astronomer, we will have to wait for the two transits of 1874 and 1882, which constituted the last adventurous undertaking relating to Venus transits.

Quoting Shakespeare, “much ado about nothing”, then? No, not at all, because the importance of that undertaking goes far beyond its astronomical results – which, in any case, were of great relevance: for example, concerning the discovery of Venus atmosphere in 1761 (Lomonosov 1761), made by the Russian polymath Mikhail Vasilyevich Lomonosov (1711-1765); or the several evidences which concretely cast doubt on the existence of an alleged satellite around Venus (Hell 1765).

In fact, the numerous expeditions led to fundamental geographical explorations and to the discovery of new lands, such as New Zealand, which was circumnavigated during Cook’s voyage (Cook 1893). Furthermore, the need to obtain the latitude and the longitude of the observing stations gave a huge impetus to the creation of extremely accurate maps of many territories. Those charts were often traced thanks to the contribution of the astronomers involved in the transits, who had skills and instruments particularly suited to the purpose, such as the accurate sea chart of the eastern region of Madagascar drawn by Le Gentil, who determined the exact geographical position of the coastlines and of the islands (Le Gentil 1779).

Furthermore, several scientific instruments were implemented and perfected: in fact, among many things, in early 1760s the English instrument maker Peter Dollond (1730-1820) invented the triple achromatic lenses (apochromatic lenses) – an improvement of the achromatic lenses invented in 1758 by his father John Dollond (1706-1761) – which strongly reduced the effects of chromatic aberration (that is, the distortion due to colour fringes) in refracting telescopes. Moreover, in those years, John Harrison (1693-1776) invented his first “sea watch” (known as H4), a long-sought-after device which allowed a giant leap forward in solving the thorny issue of calculating longitude while at sea.

And again, new remedies for some diseases were studied, including one to prevent scurvy, essential for long sea voyages (we must keep in mind that, at that time, seamen – especially those enrolled in long voyages – were usually severely afflicted with scurvy, which was the most difficult enemy to fight with). The voyage of Cook was the perfect occasion to test such a remedy, allowing the crew of *HMS Endeavour* to register just three slight cases of scorbutic disorders out of 94 crew members, on the whole outward journey (Cook 1893).

Last but not least, on the occasion of the transit of 1769, the first linguistic comparison study was carried out (Sajnovics 1770), leading to the discovery of a common root between Hungarian and Lappish (both belonging to the language family that is called, since then, Finno-Ugric).

8. The power of history

One last question still remains to be discussed, that is, why choosing to tell historians of astronomy a story that is not en+tirely satisfactory from the point of view of the astronomical results obtained (at least, as regards the main goal of this undertaking)? Actually, the answer is quite simple.

In fact, history serves as a means to emphasize how the scientific endeavour is invariably constrained by the knowledge and the technological boundaries of its era. Simultaneously, it enlightens us to the fact that science itself acts as the primary catalyst and as the driving force for expanding these limitations, both in theoretical and practical realms. Consequently, delving into the historical context becomes essential not only for comprehending the significance of a scientific pursuit but also for understanding its broader repercussions.

Furthermore, exploring the history of a scientific concept, tracing its inception and development over time, even as it grapples with setbacks and challenges (such as the arduous quest to determine the AU), grants us a more profound insight into its present-day relevance and fosters a heightened awareness.

Finally, in the specific case of this story, we also see how science has the extraordinary power to overcome disputes and national borders. In fact, collaboration and sharing are two fundamental elements for the progress of science. And in a period like the one we live in, this aspect is even more important and relevant.

9. Explicit

We have thus come to an end: here is the conclusion of this brief narration concerning the astronomical venture of the two transits of Venus of the eighteenth century.

The enterprise was massive and elaborate, and what reported in these pages is nothing more than a very small part of the whole story. In fact, many things have been recalled, but many more have purposely not even been mentioned. Undoubtedly, I could have gone into deeper details, through technical discussions, but I deliberately chose to provide a more general overview, which was able to convey the extraordinary importance and significance (not only from an astronomical point of view) of that incredible undertaking. Therefore, I hope readers will judge me kindly – quoting the words of one of the most eminent philosopher and scientist:

> non seulement des choses que iay icy expliquées; mais aussy de celles que iay omisés volontairerement, affin de leur laisser le plaisir de les inventer [not only as to the things which I have explained, but also as to those which I have intentionally omitted, so as to leave the others the pleasure of discovering them] (Descartes 1637, p. 413).

Acknowledgements

The research behind this paper would not have been possible without the exceptional support of Paola Focardi (University of Bologna), who has provided me extensive personal and professional guidance. I thus owe her a great debt of gratitude for her constant and enthusiastic encouragement while unravelling and reconstructing this colossal astronomical venture.

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