# The Transit of Mercury 2016

## and the last Transits of Venus

(For the preparation of the transit project)

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*The Observation and measuring of Venus transits in front of the Sun have for a long time been the best opportunity to determine the distance between Earth and Sun. Even if the Astronomical Unit has today been determined much more precisely the transits of 2004*[1] *and 2012*[2] *offered extraordinary opportunities to retrace the historical measurements by employing modern methods and to practise the cooperation between schools, amateurs and universities.*

*On May 9th we will try to repeat the measurement of the Sun's distance with the much smaller parallactic effect of Mercury. Therefore, this paper points to the homepage of a corresponding internet project. Reminders of the 2004 and 2012 projects and practical tips at the end of this paper try to enlarge the chance of succes.*

# 1 Introduction

On June 8th, 2004 and June 5/6th, Venus, observed from Earth, passed the Sun's face from east to west. So-called transits of Venus belong to the rarest astronomical events that can be predicted precisely. No human being living in 2004 had so far observed such an event, simply because none happened during the previous century. In fact, only five transits of Venus have been observed and described by human beings so far (1639, 1761, 1769, 1872 and 1882) and the following will happen in 2117.

Transits of Mercury are not as rare as those of Venus. The preceeding occured in 2006 and the following will happen in 2019. But to observe and evaluate transits of Mercury is more difficult as transits of Venus because Mercury is much smaller and about twice as far from Earth.Therefore, the observable parallactic effect is smaller and it will be even more difficult to measure Mercury's position in front of the Sun with sufficient accuracy.

Transits of Venus have played an important role in the development of modern astronomy because their measurements provided for the most precise measure of the Sun's distance until the end of the nineteenth century.

[1] `http://www.didaktik.physik.uni-due.de/~backhaus/VenusProject.htm`
[2] `http://www.venus2012.de`

## 2 The Astronomical Unit

In the 18th and 19th century several expeditions were equipped and launched into various distant regions of the world with the objective to provide astronomers with suitable observation data from the very rare Venus transits ([9], [21], [20]). Why did the governments of so many countries spend so much money and why were the astronomers willing to endure the harsh conditions of those expeditions ([15]) to obtain a better measure of the Sun's distance? And why is it still important to know not only the value of the Astronomical Unit but also the methods which enabled a more and more precise determination?

These tremendous efforts of governments and human beings express a large interest in the distance to the Sun. The reasons for that are scientific as well as economic:

- The distance to the Sun is the basic unit for determining the size of the whole solar system: Knowing the distance to the Sun, we can determine the size of the whole solar system. Since the introduction of the heliocentric world view it has been rather easy to determine the radii or the maior semi-axis of the planets' orbits. However, the results of these measurements reveal all the distances as multiples of the radius of the Earth's orbit. And the value of that was not very well known. For example, the doubling of the distance between Earth and Sun would have resulted in a respective enlargement of the whole solar system. But the ancient value of the Sun's distance which was used until the seventeenth century was in fact too small by a factor of 20.

- The distance to the Sun also forms the basis for measuring the distance to the stars.

- Knowing the distances in the solar system it is possible to determine the astrophysical properties of the Sun and the planets. For instance, the size of the Sun and of the planets can be deduced from their apparent size. The mass of the Sun can be calculated by the help of the law of gravity, provided that the gravitational constant is known. The radiation power of the Sun can be derived from the solar constant measured on Earth.

- As a crucial precondition for a growing worldwide sea traffic, a more precise astronomical navigation had to rely on more precise predictions of the motions of the planets. Once the absolute distances in the solar system are known it is possible to take into account the pertubations of the planets' orbits which are due to gravitational interactions between the planets. Therefore, more precise predictions of the motions of the planets and, particularly, of the moon can be made.

For these reasons, the distance to the Sun is not only a scale for the solar system and, for example, for the mass of its bodies but also for the dimension of the whole universe – the so-called Astronomical Unit.

By learning something about the history of that unit and the problems encountered by measuring it students not only gradually acquire an idea of the almost unbelievable size of the universe. This example also allows them to understand "what it means to do physics (and astronomy)" and "how it was possible in the first place (and still is today) to know those facts" (Wagenschein).

Figure 1: Stereoscopic picture of a landscape and the ruins of a building. You get a stereo effect by looking at the picture with the "parallel glance" so that the two black spots above the pictures merge into one.

Recalling the history of that Unit and underlying basic concepts, together with experiencing some of the problems encountered during measurements, does not only provide for a better understanding of former achievements. In addition, it seems to be a suitable way to gain a deeper insight about the interplay between theory and observation in science in general, and of astronomy in particular. Calculating with data that extend far beyond men's imagination might also serve for approaching a realistic perspective on contemporary developments of science.

# 3 The geometric parallax

If you hold an object, e.g. an apple, at arm's length, close your eyes one by one, you will observe the apple jumping from right to left and inversely in front of the distant objects in the environment. This apparent change of position, the so-called parallactic motion, is due to the changing perspective.

This parallactic effect is familiar to all of us from our daily experiences, e.g. with driving a car or travelling by train: The closer the objects in the landscape are, the faster they stay behind, that is to say in forward movement, they move backward in relative proportion to the more distant objects. The further the objects are, the smaller is the effect. That's why it can be used in order to determine the distance of objects.

This parallactic effect is familiar to all of us from our daily experiences: If we observe a landscape from different viewpoints all objects have different positions with respect to the others. The closer the objects in the landscape are, the more they change their relative positions. The further the objects are, the smaller is the effect. That's why parallax can be used in order to determine the distance of objects.

As a matter of fact, the parallaxe is a major precondition of three dimensional sight.

- Our two eyes take in different pictures in which the objects' relative positions to each other differ slightly. In our brain, the two pictures are transformed into a three dimensional picture (fig. 1).

- If the distances are too big and if, consequently, the parallactic differences are too small for a threedimensional picture, the enhancement of parallactic shifts caused

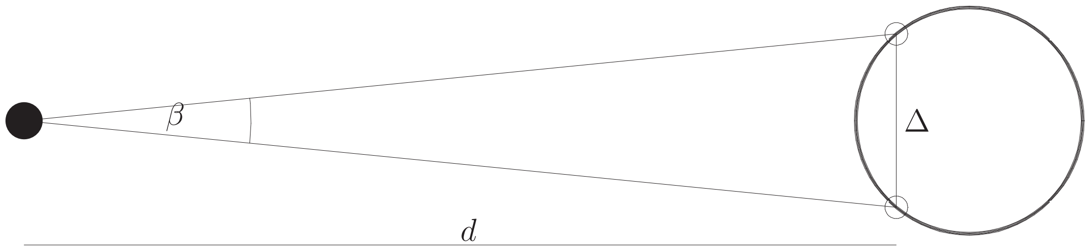


Figure 2: On the relation between parallax $\pi$, distance *Delta* between the points of observation and the distance $d$ of the object

by movement may help to get an impression of the spatial depth.

The parallax $\pi$ of an object is the difference between the perspectives of two different observers looking at it. Or to put it differently: $\pi$ is the angle by which the distance $\Delta$ of the two points of observation , e.g. the eyes or the two observatories, appear from the object's position (fig. 2). Provided that the line connecting both points of observation is perpendicular to the direction of the object, the following relation obviously holds:

$$\tan\frac{\pi}{2} = \frac{\frac{\Delta}{2}}{d} \quad\Longrightarrow\quad d = \frac{\frac{\Delta}{2}}{\tan\frac{\pi}{2}} \tag{1}$$

If the distance is very large, the parallax therefore very small, the following formula can be used as an approximation:

$$\boldsymbol{d \overset{\pi \ll 1}{\approx} \frac{\Delta}{\pi},} \tag{2}$$

where $\pi$ must be expressed in radians.

Until today, the measurement of so-called trigonometric parallaxes is the most precise procedure to determine the distance of astronomical objects.

> *The parallaxe of an object in the solar system is defined by the angle by which the Earth's radius appears from the object's position*[3].

If one observes the relative shift in position $\beta$ in front of an "infinitely" distant background, then it directly shows the parallaxe of the object: $\beta \equiv \pi$ (s. fig. 3[4]).

However, if one observes the parallactic shift with respect to a very, but not infinitely, distant background, the relative shift is smaller than the parallaxe because the background object itself shows a parallactic effect: $\beta = \pi - \pi_H$ (s. fig. 4).

[3] With regard to objects outside the solar system, e.g. the stars, the parallaxe refers to the radius of the Earth's orbit, that is to say to the distance between Sun and Earth.

[4] Figures 3 and 4 are stereoscopic pictures. You get a stereoscopic impression by looking at them with the "parallel glance" so that the two pictures seen by both eyes merge into one picture in between. The dots above the both pictures may help you: Your eyes are positioned correctly when you see one additional dot appearing exactly between both of them. It is favourable to put your eyes first very close to the pictures and then to remove them slowly until you have found the correct position.

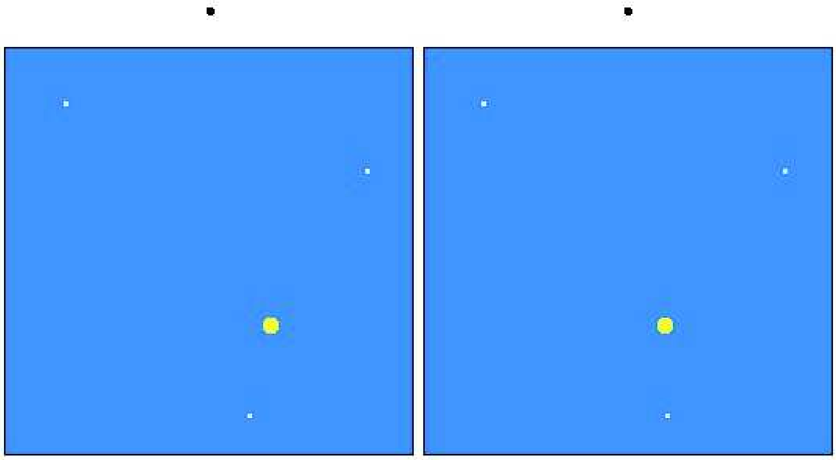

Figure 3: Parallactic shift of Venus with respect to the background of the stars. This shift equals the parallaxe of Venus $\pi_V$.

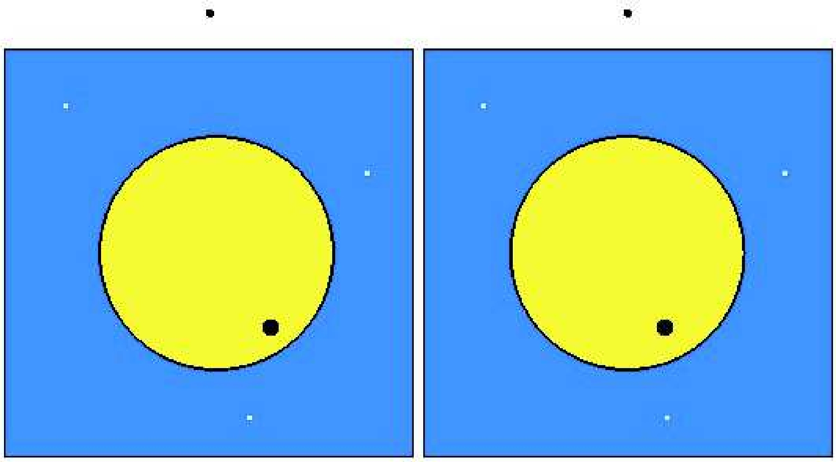

Figure 4: Parallactic shift of Venus and Sun. Because of the shift of the Sun the shift of the Venus with respect to the Sun's disc is smaller than with respect to the stars in figure 3. It corresponds to the difference $\pi_V - \pi_S$.

# 4 The parallax of the Sun

The distance to the Sun is very large, the parallax, therefore, very small: Its value is only 8".8. That is the appearent size of a little coin in a distance of 230 m! To make it more difficult, no background can be seen when the Sun is shining. Thus, it is not possible to measure the Sun's parallax directly by a geometrical method.

The basic idea of geometrically measuring the distance to the Sun is to determine the parallax of another body of the solar system and to derive from its distance that of the Sun, e.g. with the help of Kepler's third law.

The following bodies have been used:

- **Mars**, by far not as bright as the Sun and, in its opposition to the Sun, only half as far as it was the first body to translate this idea into action. Already Kepler had noticed that he could not observe any parallactic movement of Mars. From this experience, he had concluded that the distance to the Sun given by Aristarchus must be by far too small. In 1672, Cassini in Paris, Richer in Cayenne and Flamsteed in London succeeded in determining the parallactic angle of Mars to be about 25".5 and to derive a solar parallax of not more than 10".

- **Venus**, in inferior conjunction to the Sun, comes still closer to the Earth than Mars. Unfortunately, it is usually invisible in that position. But during one of the very rare transits it can be observed quite well in front of the Sun and its position with respect to the Sun's disc can be measured easily, at least in principle. Therefore, after the observation of a transit of Mercury Halley in 1716 proposed to observe and to measure the next coming transits of Venus from as many different sites on Earth as possible in order to get a measure of the distance to the Sun as precise as possible.

- During a transit even **Mercury**'s position in front of the Sun is well measurable, at least in principle. But its distance from Earth then is nearly twice as large and the parallactic effect correspondingly small.

- Some **minor planets** come even closer to the Earth than Venus. Additionally, because of their little brightness and small size their position can be determined even more exactly. In 1931, the minor planet **Eros** led to a very exact determination of the Sun's parallax[5]. But, meanwhile it had become possible to measure it by means of physical methods.

# 5 Geometry of the Transit

*This section can be applied nearly without changes to transits of Mercury.*

For two observers at different sites on Earth a transit lookes slightly different: Venus enters the Sun's disc at different times and doesn't leave it simultaneously. And, taken

[5]The determination of the distance to the Sun by measuring minor planets' parallaxes was the subject of another internet project in 1996 ([6] and [7]).

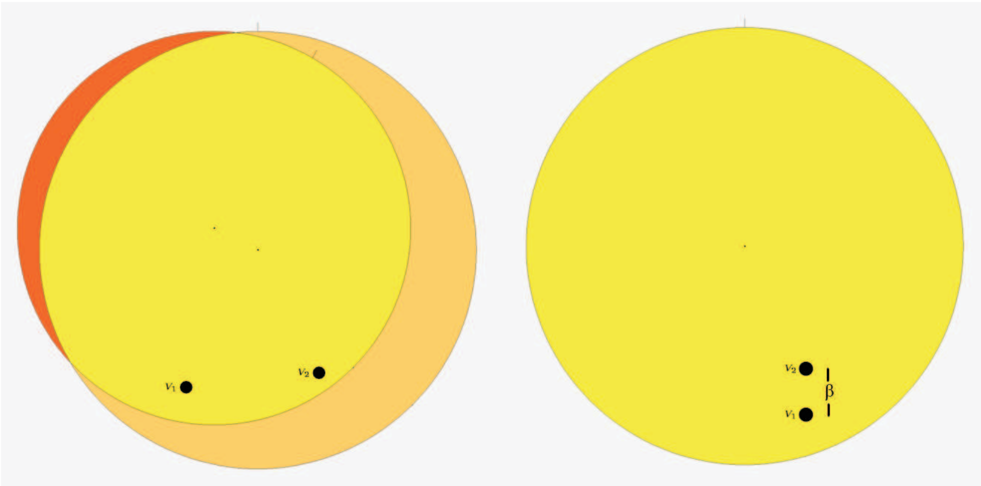


Figure 5: Two photos of Venus in front of the Sun, simultaneously taken at different sites on Earth. Left: With original size arbitrarily merged. Right: Scaled to the same size, shifted to coincidencing centres, and rotated to the same orientation. The parallactic effect is strongly exaggerated.

at the same moment, Venus' position in front of the Sun is not quite the same. This parallactic effect can be observed

- if the length of Venus' path over the Sun is determined by precisely measuring the moments of ingress and egress (**contact times**) or
- if two simultaneously taken photos are scaled to the same size and merged with exactly the same orientation (fig. 5).

> *How is it possible to infer the distance of Venus from Earth and finally, the distance between Earth and Sun from this parallactic shift?*

The parallactic shift between both discs or between both paths of transit is most often explained in the following way: Because Venus divides the distance Earth - Sun by 5:2 (Mercury: 4:5) the distance between the two "projections" on the Sun must be 2.5 times as large as the separation of both observers. Therefore, the angular distance between these projections, when observed from the Earth must be 2.5 (Mercury: 0.8) times as large as the distance of both observers appears to an observer on the Sun. In the situation shown in figure 7 the angular distance of the projections ("shadows") is, therefore, five times as large as the angle by which the *Earth's radius* is seen from the Sun, the so-called parallax $\pi_S$ of the Sun.

This explanation appears to be plausible. Nevertheless, there arise some questions:

1. Why does $\beta$ represent the parallactic displacement of Venus instead of $\beta_V$?
2. Of course, on the Sun's surface there are no "shadows" of Venus. How is it, nevertheless, possible to observe their distance from Earth?

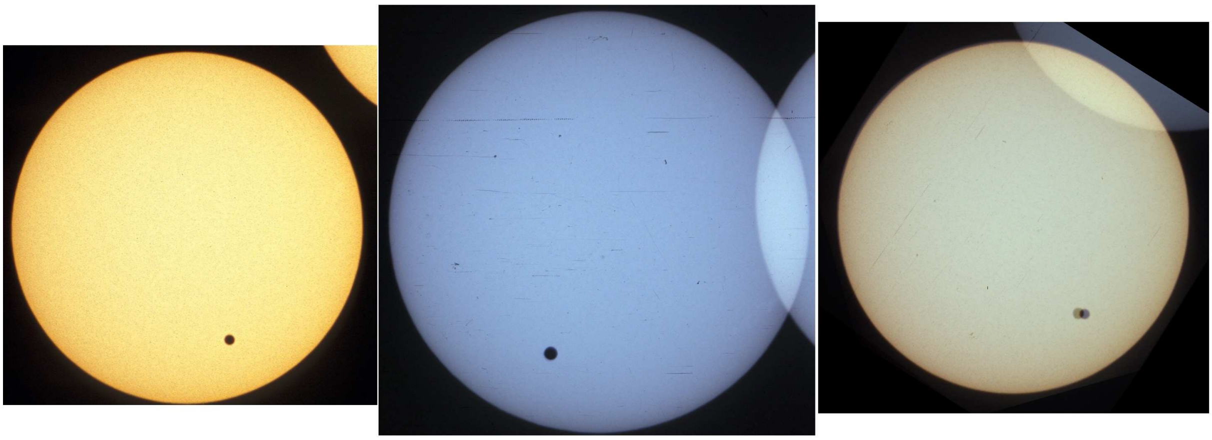

Figure 6: Photos of the 2004 transit, made from Namibia and Germany. They correspond to Fig. 5

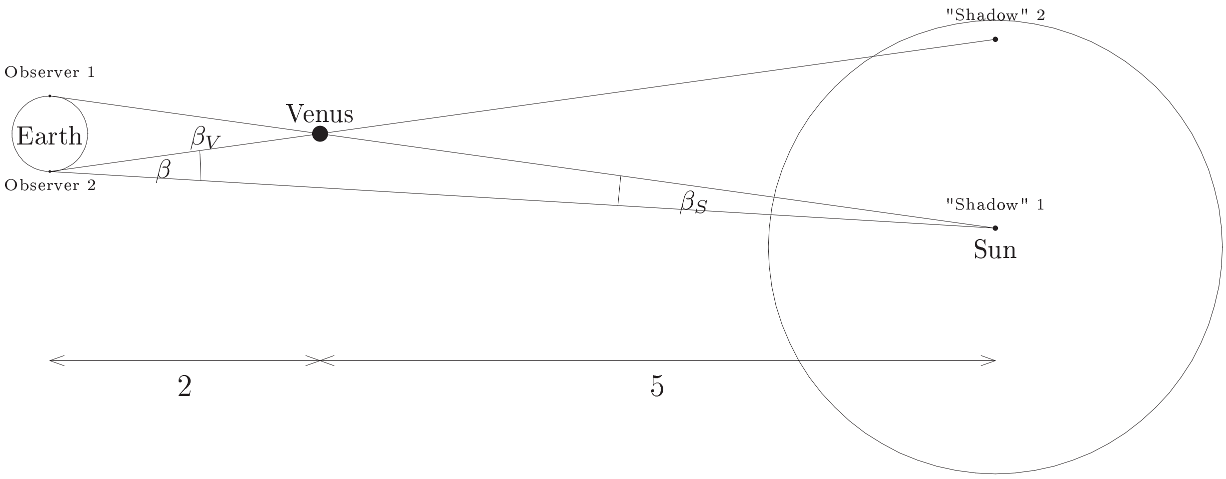


Figure 7: Usual explanation for the displacement of the two discs of Venus (e.g. Herrmann ([11])): From Earth, the distance of both "projections" of Venus is seen by the angle $\beta$. Because that distance is 2.5 (Mercury: 0.8) times as large as the distance between the both observers, $\beta$, too, is 2.5 (Mercury: 0.8) times as large as the angle $\beta_S$ by which the Earth appears from the Sun.

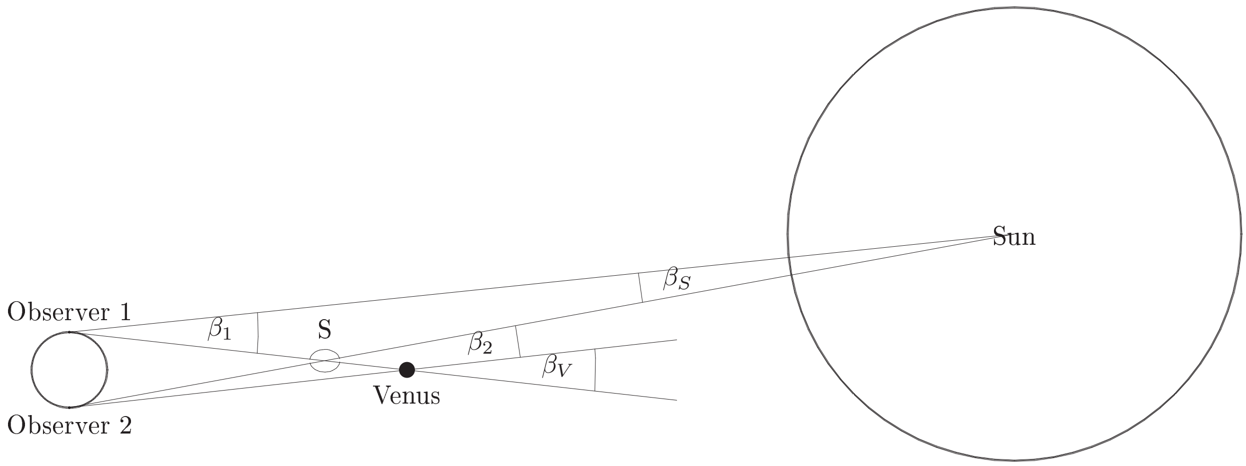


Figure 8: Alternative explanation: Different observers see Venus at different positions relative to the Sun's face. Their angular distance with respect to the Sun is $\beta = \beta_1 - \beta_2$.

3. If it is, nevertheless, possible to see those projections by some method: Are they located on the surface or on a plane, for instance, throught the centre of the Sun? What is the orientation of that plane? Because the Sun's radius is about 0.5% of the distance between Earth and Sun, the answer to this question may be of some importance.

4. When observed from Earth the position of the Sun against the stars is a little different, too. Must this effect not be taken into account?

In fact, it is neither possible to see Venus *in front of the Sun* nor to observe "shadows" *on its surface*. Instead, only angles can be observed and measured at the celestial sphere. Therefore, for both observers, Venus in figure 5 has different angular positions with respect to the Sun's face, e.g. different angular distances $\beta_1$ or $\beta_2$ from the centre (fig. 8)[6]. These angles can be taken from figure 5, provided the scale has been determined with the known angular diameter of the Sun. The distance of the two discs against the Sun is, therefore, the angular difference $\boldsymbol{\beta = \beta_1 - \beta_2}$.

Therefore, the angle $\beta$ can not be measured absolutely but only by two measurements from different sites *with respect to the Sun's face*. In contrast to the first impression, it is not the parallax of Venus but, instead, smaler than it by the parallax of the Sun! With the remarks made in section 3 this fact is clear because the angles are not measured with respect to infinitely far stars but with respect to the Sun showing parallax by itself.

This interrelation may additionally be illustrated as follows (fig. 9): Merging the pictures of the Sun taken by two observers both discs of Venus have the distance $\beta$. But, to put the pictures of the Sun into the correct position with respect to the stars one of

[6] Generally, both observers, Venus and the centre of the Sun will not be positioned in the same plane. Therefore, in fig. 5 both discs will not be located on the same radius. In that case, the two observers and Venus will define the plane of fig. 8. The argumentation remains unaltered: The difference $\beta$ is then due a point of the Sun in that plane (see also fig. 9.

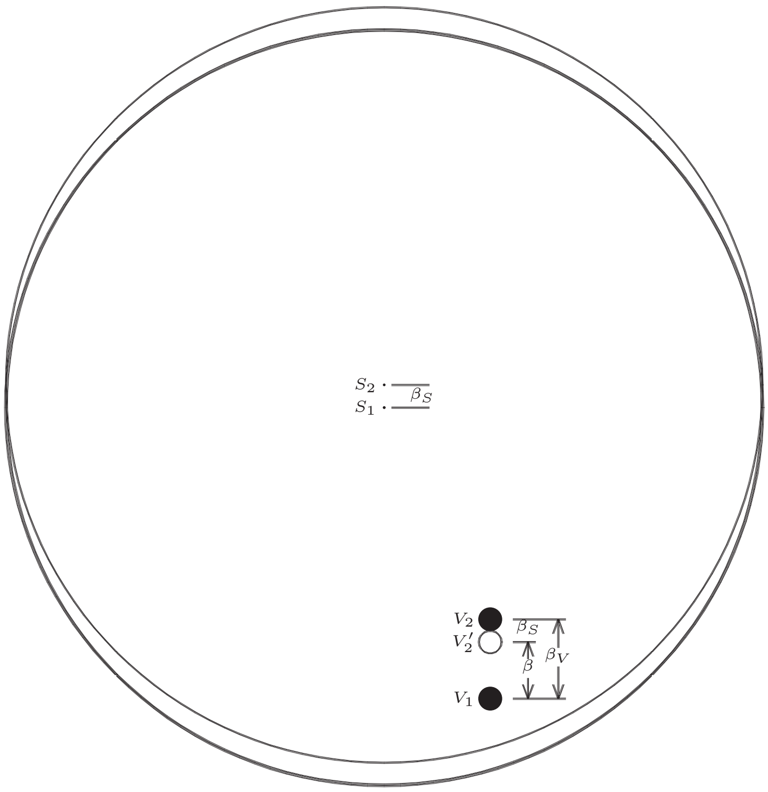


Figure 9: The pictures of the respective observers against a (fictive) background of stars: Both pictures of the Sun are shifted with respect to each other by the Sun's angle of parallax $\beta_S$, the pictures of Venus by $\beta_V$ *in the same direction*. After having shifted one of the photos so that the pictures of the Sun coincide the Venus positions differ only by $\beta = \beta_V - \beta_S$.

the pictures must be shifted by $\beta_S$. Then, $\beta_V$ will be the distance of the two discs and, therefore, larger than $\beta$ by $\beta_S$.

Let $\beta_S$ and $\beta_V$ be the angles by which the distance of the both observers appears from the Sun and from Venus, respectively, that means the actual angles of parallax of Sun and Venus. Then, due to figure 8 the following equation holds:

$$\beta_S + \beta_1 = \beta_V + \beta_2 \tag{3}$$

That is why both sums complete the opposite angles at $S$ to 180°, first in the triangle observer 1 - $S$ - center of the Sun and, second, in the triangle observer 2 - $S$ - Venus. That relation can be written as follows[7]:

$$\beta = \beta_1 - \beta_2 = \beta_V - \beta_S \tag{4}$$

[7]The same relation may be taken from fig. 7.

# 6 Derivation of the distance to the Sun

The determination of the distance to the Sun is based on the following train of thought:

- To calculate the distance to the Sun it is necessary to know the parallax $\pi_S$ of the Sun, that means the angle by which the Earth's radius appears from the Sun.
- Equally suitably is the angle $\beta_S$ by which the distance of two arbitrary observers appears from the Sun provided their distance is known.
- Instead of $\beta_S$, the larger angle $\beta_V$ by which the distance of the both observers appears from Venus can be measured more easily. Knowing the proportion between the distances of Sun, Venus and Earth (which can be determined by measuring the maximum angular distance between Venus and Sun[8])) one of these angles can be derived from the other.
- The angle $\beta_V$ is located at Venus, but it can be derived from the angles $\beta_1$ and $\beta_2$ which can be measured from Earth.

## 6.1 Theory

Because the distances of Venus and Sun from the Earth are very large compared with the Earth's radius and because the corresponding parallaxes, therefore, are very small, the angles of parallax are inversely proportional to the corresponding distances $d_V$ and $d_S$:

$$\frac{\beta_V}{\beta_S} = \frac{d_S}{d_V} \tag{5}$$

Let $r_E$ and $r_V$ be the radii of the orbits of Earth and Venus, respectively. Then the following equation follows from (4):

$$\begin{aligned} \beta &= \frac{r_E}{r_E - r_V}\beta_S - \beta_S = \frac{r_V}{r_E - r_V}\beta_S \\ \Longrightarrow \quad \beta_S &= \left(\frac{r_E}{r_V} - 1\right)\beta \end{aligned} \tag{6}$$

In practice, the angle $\beta$ is not measured absolutely but as a fraction $f$ of the angular radius $\rho_S$ of the Sun:

$$\beta = \frac{\beta}{\rho_S}\rho_S = f\rho_S \tag{7}$$

In the special case shown in fig. 7 and 8 the distance between the observers is as large as the *diameter of the Earth* and, therefore, the angle of parallax $\beta_S$ is twice the parallax of the Sun $\pi_S$ which is related to the *Earth's radius*. In general, one must know the distance $\Delta$ between the observers as a multiple of the Earth's radius, to be more

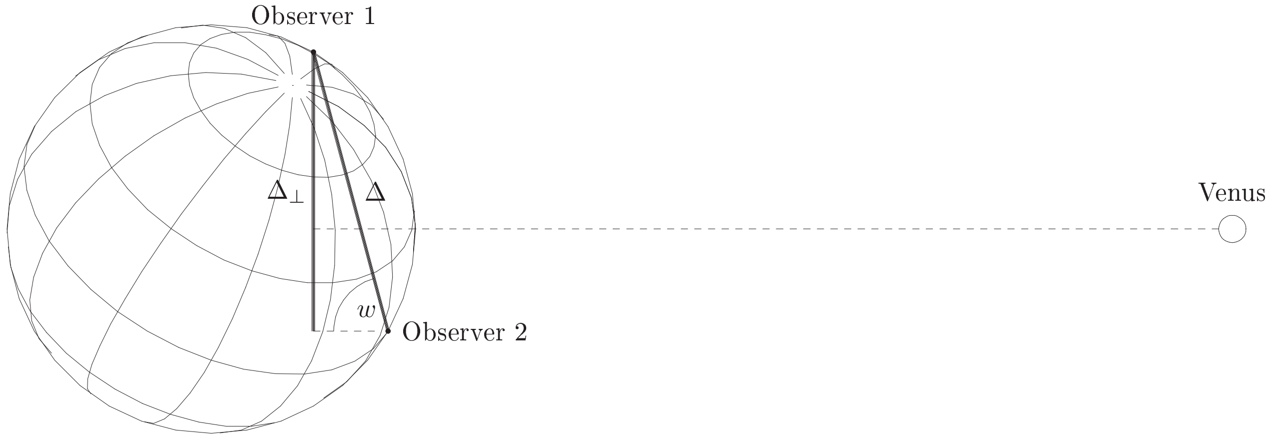


Figure 10: Not the distance $\Delta$ between the both observers itself is important for the determination of the Sun's parallax but its projection $\Delta_\perp$ parallel to the direction to Venus.

precisely: the projected distance $\Delta_\perp$ of the two observers *perpendicular* to the direction to Venus (fig. 10).

Therefore, the following equations must hold

$$\beta_S = \pi_S \frac{\Delta_\perp}{R_E} = \pi_S \frac{\Delta}{R_E} \sin w \quad \Longrightarrow \quad \pi_S = \frac{R_E}{\Delta} \frac{1}{\sin w} \beta_S$$

and, finally,

$$\boldsymbol{\pi_S = \left[ \frac{R_E}{\Delta} \frac{1}{\sin w} \left( \frac{r_E}{r_V} - 1 \right) \rho_S \right] f.} \tag{8}$$

From this result for the parralax of the Sun $\pi_S$, the distance to the Sun, the so-called **Astronomical Unit (AU)**, can be derived by the following equation (see (2)):

$$\boldsymbol{1AU = d_S = \frac{R_E}{\pi_S}} \tag{9}$$

The results of these equations can be improved by using the actual values of the orbit's radii (instead of the mean values) and by taking into account that the solar parallax $\pi_S$ in equation (8 doesn't refer to the Astronomical Unit (that is the mean value of the distance Earth - Sun) but to the *actual value on transit day.*

## 6.2 An Example

Two pictures of the transit of Venus on June 8th, 2004 may be given, simultaneously taken from Essen, Germany, and from the Internationale Amateur Sternwarte IAS near

[8] as we did in 2004 (`http://didaktik.physik.uni-essen.de/~backhaus/Venusproject/venusorbit.htm`

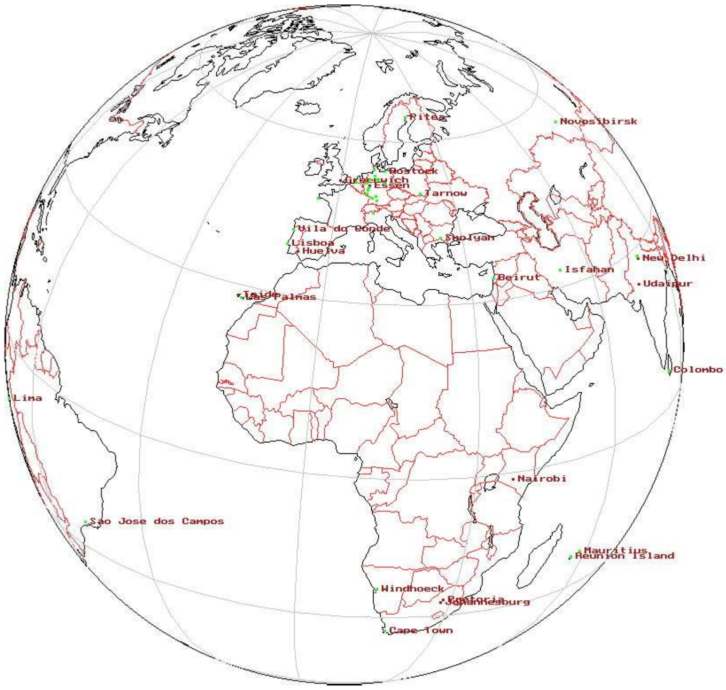


Figure 11: Daylight side of the Earth at 8:00 UT

Windhoek, Namibia, respectively, at 8 .00 UT (from `http://www.venus2012.de/venusprojects/photography/example/example.php`, see also Fig. 6).

1. On these pictures, the distance between the both discs of Venus can be measured to be quite exactly 2.7% of the radius of the Sun ($f = 0.027$). On that day, the angular radius of the Sun was $\rho_S = 15'.66$. Therefore, the angular distance $\beta$ of the two discs is

$$\beta = f\rho_S = 25''.73$$

2. The (average) distance between Earth and Sun is $r_E = 1.0AU$, the (average) distance between Venus and Sun $r_V = 0.723AU$ ($\frac{r_E}{r_V} - 1 = 0.383$).

   Therefore, according to equ. (6), the angular distance between the both cities seen from the Sun is

$$\beta_S = \left(\frac{r_E}{r_V} - 1\right)\beta = 9''.86.$$

3. The projected distance $\Delta \sin w$ between the cities can be derived from their geographical coordinates and the time of the images. But here we will take it from figure 11 which show the Earth's daylight side at that moment:

$$\Delta_\perp = 1.19R_E.$$

4. Putting these results into equ. (8) we get the final result:

$$\boldsymbol{\pi_S = 8''.30}$$

and for the distance between Earth and Sun

$$d_S = 24860 R_E.$$

These results can be improved by taking the *actual* values of the distances ($rE = 1.015AU, r_V = 0.726 \implies \frac{r_E}{r_V} - 1 = 0.398$) and the correct radius of the Sun ($\rho_S = 15'.76$) instead of the average and measured values. Then we get

$$\pi_S = 8''.62 \text{ and } 1AU = 23920 R_E.$$

# 7 Measurements and Calculations

The equations (8) and (9) summarize how it is possible to get a value for the distance to the Sun by observing and measuring a transit of Venus. They make clear what must be measured and what must be calculated in order to determine the parallax of the Sun:

$$\boldsymbol{\begin{aligned} \pi_S &= \left[\frac{R_E}{\Delta}\frac{1}{\sin w}\left(\frac{r_E}{r_V} - 1\right)\right]\beta \\ 1AU &= d_S = \frac{R_E}{\pi_S} \end{aligned}}$$

- The basic measure is the **angular distance $\boldsymbol{\beta}$** of the discs of Venus on transit photos simultaneously taken from distant places on Earth (e. g. Europe, India and South America). The positions must be measured with respect to the Sun's disc. If this measurements have been done properly the further evaluation is possible with elementary mathematics only.

  The planet's position depends not only from its distance to the Sun's edge (or its centre) but from the direction from the Sun's centre, too. Therefore, the exact orientation of the images must be known. One possibility for this determination is to exposure the images twice *with fixed camera* with only few minutes time difference[9]. The translation of the Sun caused by the Earth's rotation then indicates the direction from east to west.

- First, that angular distance is determined as a **fraction $\boldsymbol{f}$** of the Sun's angular radius. In order to transform $f$ into an absolute angle the **angular radius $\boldsymbol{\rho_S}$** of the Sun must be determined.

$$\boldsymbol{\beta = f\rho_S.}$$

[9] or later to combine two images which have been taken successively

- In order to infer the parallax of the Sun from the actual parallax angle, the **linear distance $\boldsymbol{\Delta}$** of the both observers must be determined as a **multiple $\boldsymbol{\frac{\Delta}{R_E}}$** of the Earth's radius. For this reason, the **geographical coordinates $(\boldsymbol{\varphi_i, \lambda_i})$** of the observers must be known.

- Not the distance of the observers itself is of importance but its projection $\boldsymbol{\Delta \sin w}$ parallel to the direction Earth - Sun. Therefore, the **angle of projection $\boldsymbol{w}$** at the time of exposure must be determined. Because it is a little bit tricky to calculated that angle[10], we here measure the projected distance in a picture showing the Earth's daylight side at that time (Fig. 11) or transmit the job to the resources (programs or Excel-sheets).

- In order to conclude from Venus' angle of parallax $\beta_V$ to that of the Sun $\beta_S$ the **radius of Venus' orbit** must be known in relation $\boldsymbol{\frac{r_V}{r_E}}$ to the Earth's radius.

- Finally, to be able to derive the distance to the Sun in absolute terms one must know the value of the **Earth's radius $\boldsymbol{R_E}$**.

- If there will be no images taken which are sufficiently simultaneous to the own ones, every participant should take as many transit pictures as possible. Then it will be possible later to calculate a linear fit to all measured positions $\boldsymbol{(x_i(t), y_i(t))}$,

$$\begin{aligned} \boldsymbol{x(t)} &= \boldsymbol{at + x_0}, \\ \boldsymbol{y(t)} &= \boldsymbol{bt + y_0}, \end{aligned}$$

  so that intermediate positions can be calculated for arbitrary moments. For this task an Excel sheet has been placed at the disposal[11].

# 8 The internet projects

## 8.1 The Transit of Venus 2004

It was the main objective of the project of 2004[12] to bring into contact school classes, astronomical work groups, groups of astronomical amateurs and observatories in order to corporately observe and photograph the transit of Venus in 2004 and to derive the distance to the Sun from own data by different methods. Afterwards, the material has been arranged so that it offers possibilities for evaluation with different claims for exactness in education.

The months before the transit have been used as a comprehensive educational project. Within the framework of the developing international cooperation all quantities which are explicitly or implicitly contained in equations (8) and (9) have been determined by own measurements.

To obtain this goal the following projects of preparation have been created:

[10] http://www.didaktik.physik.uni-due.de/~backhaus/Venusproject/geogrpositions.htm
[11] http://www.venus.de/transit-of-mercury2016/stuff/tableofMercurypositions.xls
[12] http://www.didaktik.physik.uni-due.de/~backhaus/VenusProject.htm

**Measuring the radius of Venus' orbit** The radius of the orbit has been determined by measuring the largest elongation of Venus before and after the transit. The observation of Venus' retrograde motion offered a second possibilty for this task.

**Determining of the own geographical coordinates and the projected distance of different observers** The participants measured their own geographical coordinates by using a radio controlled clock and a gnomon.

**Determining the radius of the Earth** By using the same simple equipment the Earth's radius has been measured for instance between Iran and Germany, but even within Germany ([1], in German).

**Measuring the angular radius of the Sun** We used the size of "Sonnentalern" (pinhole images of the Sun) and the movement of projected images of the Sun. But mainly we measured the radius by evaluating twice exposed images of the Sun.

**Exercises in photographing the Sun and exact position measurements on the Sun's disc (Sunspots)** The experiences won in this project proved to be of unique significance. Several partners which not had participated in this preparation were not aware of the critical aspects of the photographing procedure. Therefore, their images could not be evaluated.

**The Transit of Mercury on May 7th, 2003** This transit mainly served as preparation especially of the photographing procedure and as test of the mathematical algorithms. The algorithms proved to be correct but could be improved and the participants of 2003 could use their experiences in 2004.

## 8.2 The Transit of Venus 2012

The transit project of 2012[13] was a repetition of the project of 2004. But the transit in 2012 happened at times which were unconvenient for Europe. Additionally, the weather in Europe was far from optimal for observing the transit. Therefore, only a small number of people took part in the project.

Different from 2004 we passed the projects of preparation. As a consequence most of the participants did not comply with our tips and time proposals. Most of them didn't take twice exposed pictures and nearly no pictures had been taken at the same time. Nevertheless, both problems could finally be solved:

- Prominent sunspots helped us to determine the orientation of the images although not as accurately as would have been possible with twice exposed pictures.
- NASA's solar telescope SDO ("Solar Dynamics Observatory") orbiting around the Earth synchronously with the Earth's rotation took perfect images of the Sun with a times difference of only about 15s. Among them we found those which had been taken simultaneously with the images of our participants. However, the corresponding baselengths between observer and telescope had to be calculated seperately.

[13] http://www.venus2012.de

- Some of the participants submitted series of images which allowed fitting the positions of Venus to a straight line. Therefore, the positions of Venus at the appointed times could be calculated by interpolation.

The not very numerous but throughout quite good results have been collected on a results page.

In 2012 we initiated a second transit project[14] within the main project requesting the paticipants to measure the **contact times** of Venus as precisely as possible and to transmit their results to the corresponding pages for data exchange. The basic idea and the mathematical details have been described on related pages and utilities for evaluating have been provided. The results of measurements were not very numerous. But the paticipants obviously had measured very carefully. The measured contact times allowed the derivation of very good values for the distance to the Sun which differ from the correct value by less than 1%.

The results of both projects have been presented on meetings in Germany and published in a German journal ([4]). The method of contact times and the results of measurements have been converted to a task in our "Astronomical Laboratory for bad Weather"[15].

## 8.3 The Transit of Mercury 2016

The transit of this year will happen under circumstances which are very similar to those of the transit of Mercury in 2003 and of Venus in 2004. The special challenge due to the coming transit of Mercury arises by the facts that Mercury will appear much smaller than Venus and due to its nearly twice as large distance from Earth its parallactic displacement will be much smaller.

***Will it be possible to take and to gather sufficiently many and good photos which allow to make the parallax of Mercury* visible *and the distance to the Sun* determinable *by measuring Mercury's positions?***

Because the effect to be observed will be as tiny (see Fig. 12) it will be of particular importance that the baselength is as long as possible, that means that images can be compared which have been taken at places as distant from each other as possible. As the pictures on the project's homepage[16] visualize combinations as India-North America, Northern Europe-South Africa or Scandinavia-South America would be particularly advantegeous. Up to now we have found nearly no participants in North America and Scandinavia.

The following points will be of special importance for the result of the project:

- To be able to compare images taken by different observers the following data must be known as precisely as possible:
  - the **time at which the image has been taken**: *Please, adjust the camera's clock to (the second of) the GPS time shortly before the transit.*

[14] `http://www.venus2012.de/venusprojects/contacttimes/contacttimes.php`
[15] `http://www.didaktik.physik.uni-duisburg-essen.de/~backhaus/AstroPraktikum/`
[16] `http://www.venus2012.de/transit-of-mercury2016`

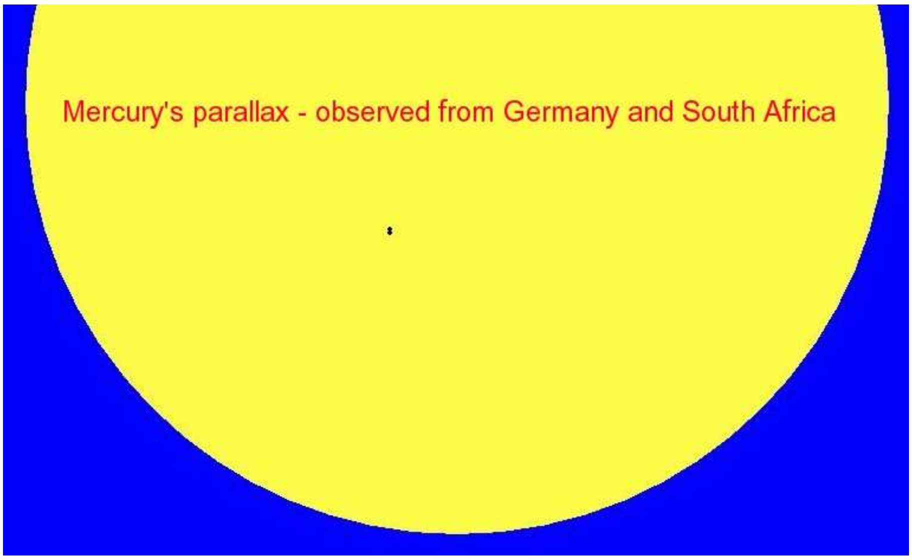


Figure 12: The (nearly) maximal size of Mercury's parallactic displacement

- the **observer's geographical psosition**: *Please, measure the GPS position in advance.*
- the **scale of the images**, it can be determined by measuring the Sun's radius on the picture. Therefore, the picture should show a big part of the Sun, the whole Sun if possible. The most exact possibility of measuring the scale is to measure the displacement between the two images of the Sun on the twice exposed photos with known time difference $\Delta t$.
- the **orientation of the images** – not easily to be determined by amateurs with sufficient accuracy. One possibility is *always to take two images with a fixed camera with a time difference of about 150s.* If an autotracking is used which cannot be switched off for a short time some parallactic mountings allow to shift the right ascension slightly so that the direction of right ascension can be determined.

  *Caused by the problem of determining the orientation the transit project of 2012 would have failed if no prominent sunspots had allowed to fix the orientation.*

- The comparation of simultaneously taken images is the best way to visualize the effect of parallax. For this reason, we have arranged several common points of time for taking pictures if possible.
- Observers who cannot use these common times for some reason nevertheless should take as many pictures as possible and measure the belonging positions of Mercury. Later these positions can be fitted to a line allowing to interpolate positions for arbitrary times.
- If possible, the participants by themselves should measure the positions of Mercury on their images, for instance with the provided tools and transmit the results to our

data exchange page.

*By comparing their own position results with those of distant observers the participants can calculate values* of their own *of the distance to the Sun.*

- Selected pictures can be uploaded to our data base, again via the data exchange page, in order to make them available for the other participants. Complete series of images should be sent to the author who will publish them on an extra project page.

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