Twilight phenomena in the atmosphere of Venus
during the 2004 inferior conjunction

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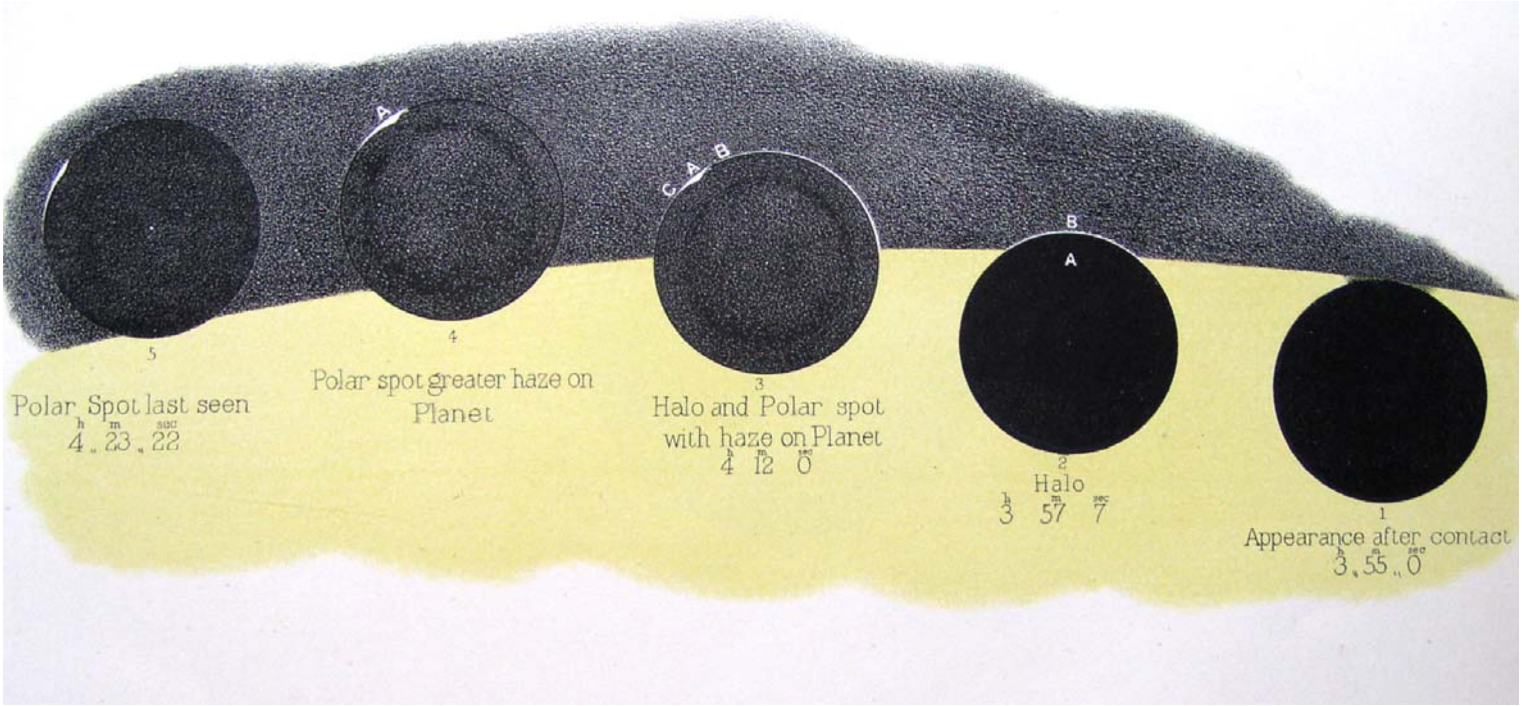

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Abstract - Twilight phenomena of Venus are peculiar aspects visible in proximity of the inferior conjunctions of the planet. They include the refraction image of the Sun that has been observed during the planet transits, and the cusp extensions observable at greater elongations. Those two phenomena have deeply different origins, the first being ascribed to refraction, the second to scattering by a thin layer of aerosols. In the following we briefly summarize the historical record of observations, giving some physical considerations and practical advices for observation close to the June 2004 Venus conjunction with the Sun.

Introduction

The transit of the planet Venus across the Sun allows us to observe in detail some phenomena that inspired several scientific speculations in the past.

Starting from the end of the 19th century, the observers have reported some peculiar phenomena promptly attributed to Venus atmosphere: among them, in particular, the outstanding cusp extension, that tends to transform the thin crescent of Venus, close to inferior conjunctions, into a ring of light.

However, the most relevant features have been reported from past transits on the Sun, when a bright arc (aureola) all around the circumference of the planet disk has sometimes been detected.

Since both those phenomena (aureola and cusp extension) are due to something happening close to the planet terminator, they have been called "twilight phenomena". If their origin is known – the atmosphere of the planet – it is less known that the physical mechanism causing them is completely different.

The atmosphere of Venus during transits

Starting with the 1761 event, several observers has signalled the presence of an "aureola" around the planet disk, i.e. a luminescent arc running all around Venus globe, or limited to the portion projected beyond the Sun's limb, against the sky.

Often, when Venus was partially external to the Sun disk, the bright arc has appeared broken in segments, reduced in extension or limited to a single bright point (Fig. 1, 2). For simplicity we call in the following "phase" (f) the fraction of Venus diameter external to the solar disk. A value f=0 correspond to the planet entirely projected on the Sun, tangent to its border. When f=0.5, the planet centre will be exactly on the solar limb.

In the past the aureola was immediately attributed to Venus atmosphere. Following several efforts for determining the position of its rotation axis, it was verified that the bright region observable at the highest values of f corresponded approximately to the position of the poles [1]. In the 50s Kuiper [2] employed ultraviolet photography for studying the atmospheric structures, obtaining a more solid confirmation of the poles position.

Observations in the past can allow us to roughly estimate the relevant phases at which peculiar aspects have showed up.

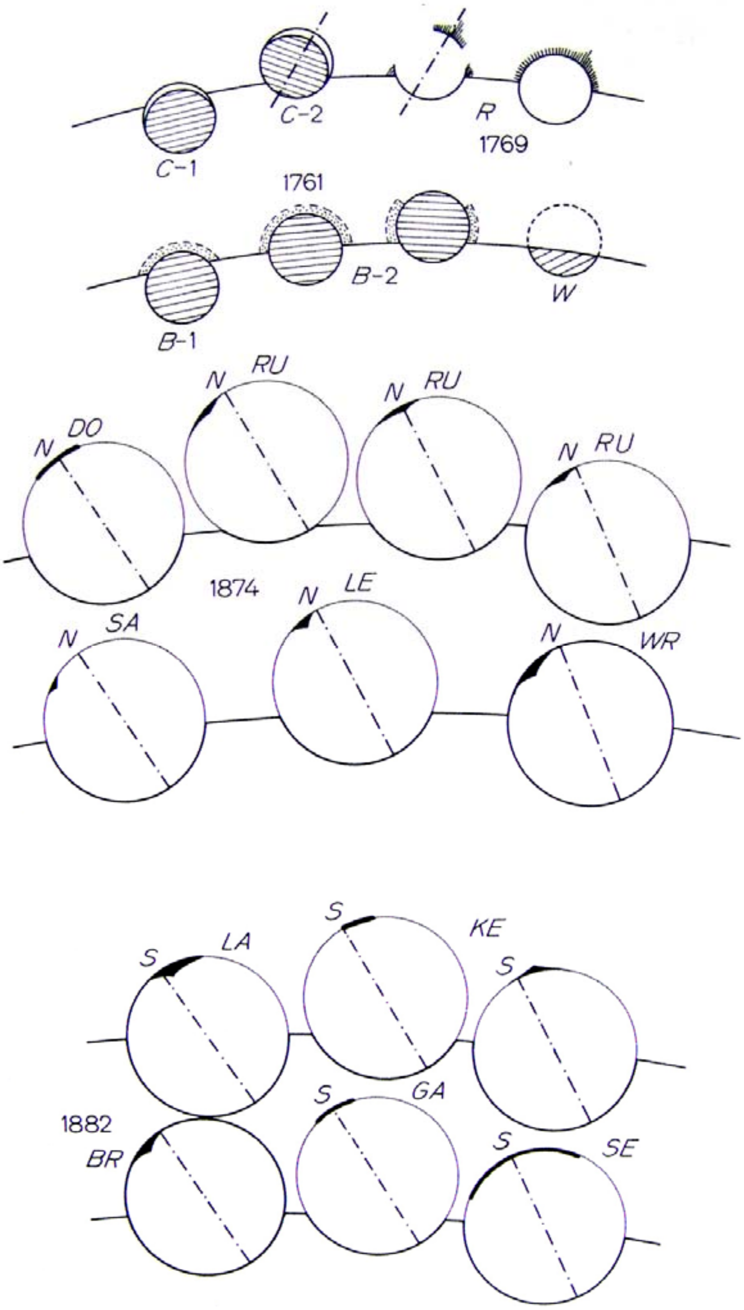

Figure 1 – A graphic summary of anomalous aspects of Venus during the ingress or egress phases of the most recent transits (1761-1882) [1]. Bright arcs (segments in black) and diffuse halos (dotted, dashed lines) are underlined. Abbreviations are referred to different observers: C: Chappe d'Auteroche; B: Bergmann; W: Wargentin; DO: Döllen; Ru: Russell; Sa: Savage; Le: Leneham; Wr: Wright; La: Langley; Ke: Keeler; Br: Brashear; Ga: Garnier; Se: Seeliger.

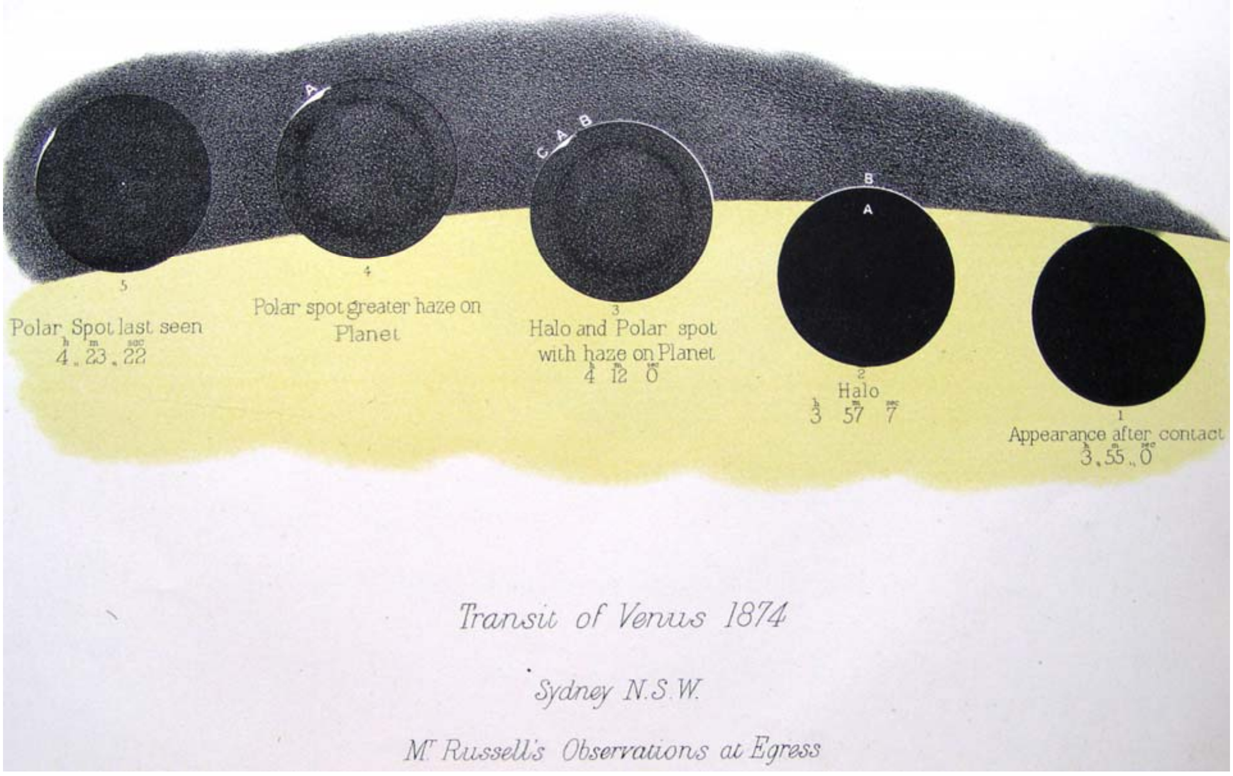

Figure 2 – Bight halos at the limb of Venus as drawn by H.N. Russell during the exit of the transit in 1874. Time increases from right to left. The gradual passage from the black drop to a luminescent arc beyond the limb of the Sun is represented. The arc reduces to a segment whose position is close to the north pole of the planet.

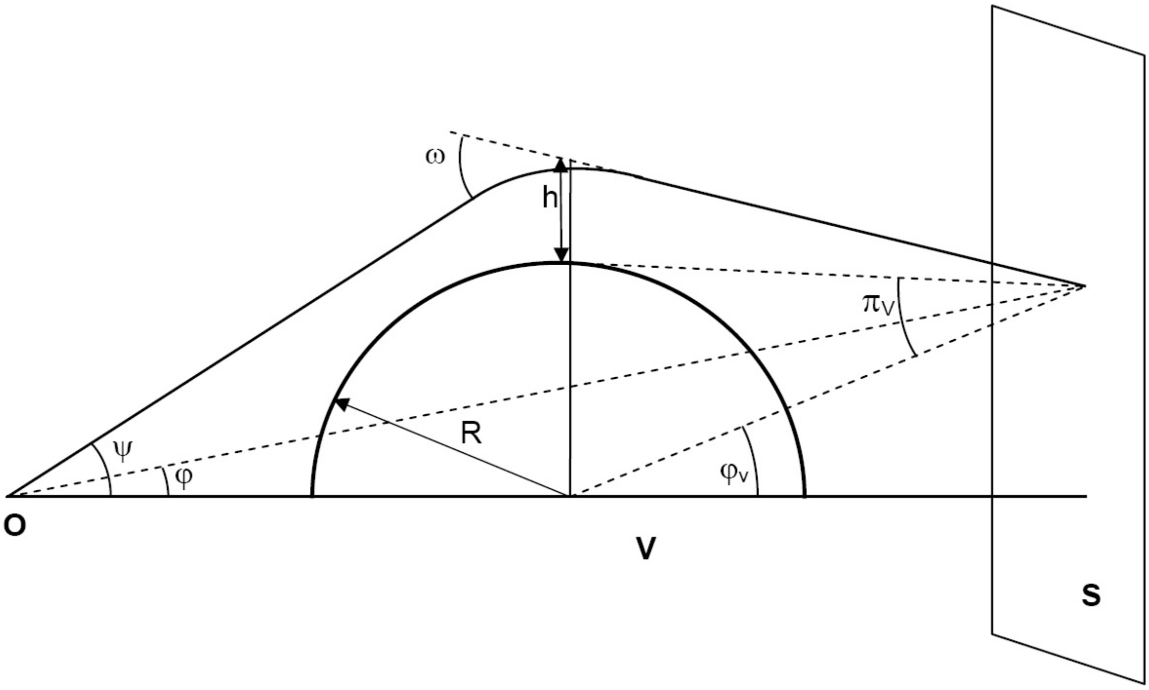

Figure 3 – Path of a sunlight ray through the atmosphere of Venus, during the transit. See the text for a detailed explaination.

The values of f (Table 1) thus obtained offer some useful indications.

Table 1

Phenomena	*phase*
Aureola visible	0.10 – 0.40
Aureola more intense close to a pole	0.22 – 0.37
Closure of opening of the aureola	0.30 – 0.50
Disappearance of appearance of the aureola	0.50 – 0.67
Formation of the polar spot	0.62 – 0.81
Bright spots visible	0.55 – 0.70
Venus disk visible outside the Sun, surrounded by an aureola.	0.56 – 0.98

The observations can be satisfactorily interpreted and explained if the refraction of light inside Venus atmosphere is invoked. In the following we will explain a simple model that allows to better understand the phenomena and to formulate some predictions for the 2004 opportunity.

Refraction in Venus atmosphere.

The optical path of the light rays coming from the Sun can be schematically represented as in Fig. 3, in which only one hemisphere of Venus (V) has been drawn; the situation will be symmetrical for the opposite hemisphere. On the right S indicates the solar photosphere; the Earth-based observer is in O. The radius of Venus is indicated by R. For sake of clarity all angles have been greatly exaggerated and proportions are not respected. The light ray reaching O has been emitted from S and deviated by refraction inside Venus atmosphere.

During the passage inside atmospheric layers of different density, the ray will follow a complex path, roughly curvilinear. Since density depends from the height of the layer, the deviation will be stronger at the deeper levels. For this reason, the observer collects rays that have followed different paths, and an extended region of the photosphere will contribute to the bright halo seen at the planet limb. The inferior and superior limits of the concerned atmospheric region are determined by the physical characteristics of the latter. We indicate with h the height of the rays projected on the line perpendicular to the O-V-S direction (Fig. 3).

ψ is the angle (apparent distance) between the planet centre and the direction of the incoming light ray, as seen from the observer. This angle is in general very close to the apparent diameter of Venus as seen from the Earth (ψ_V). φ is the angular distance between the O-V direction and the starting point of the ray. Finally, it is useful to define the apparent radius of Venus as seen from the Sun: π_V.

The angular distance between the O-V direction and the starting point of the light ray, as seen from Venus, will be given by:

$$\varphi_v = \pi_v\left(1+\frac{h}{R}\right)+\psi-\omega\,,$$

in which ω is the angle of deviation of the ray.

Since we are interested to the Earth observer, that angle will be reduced of a factor corresponding to the ration of the distances Venus-Sun and Earth-Venus. Expressing it in terms of apparent diameters, we will have:

$$\varphi = \varphi_v \frac{\psi_v}{\psi_v + \pi_v}\,.$$

Given the values of the semimajor axis of Venus and Earth orbits (we neglect here the eccentricity) we will have, on average:

$$\varphi = 0.725\cdot\varphi_v\,.$$

In conclusion, the angular distance between the centre of Venus disk and the original direction of the light ray will be:

$$\psi = \psi_v \left(1 + \frac{h}{R} \right).$$

These simple equations allow us to describe the solar image formed by refraction in the atmosphere of Venus.

First of all, it must be noted that the apparent angular size of Venus is small (close to 1 arc minute), so all deviations are extremely small. Furthermore, the atmospheric layer is much smaller than R, so that also h<<R. Let's consider the ray passing at the lowest possible height, grazing the opaque layer. It will be justified to assume h=0.

The equations, referred now to that critical level can be rewritten as follows; for the observer on Venus:

$$\varphi_v(0) = \pi_v + \psi_v - \omega(0).$$

For the Earth based observer:

$$\varphi(0) = \psi_v - 0.725 \cdot \omega(0),$$

in which the (0) indicates that quantities are referred to the critical layer h=0.

The Sun's refracted image

The values of ω (in general) and ω(0) (in particular) depend upon the refraction index of the atmosphere. Let's assume as a first approximation that the refraction properties do not depend from the position on the planet: this simplification allows understanding some geometrical bases of the problem. In fact, in that case, at any place along the limb of Venus disk the angles maintain the same values. If we consider the Sun as a flat, distant radiating surface (S), perpendicular to the direction O-V, we can see that the light refracted at h=0 comes from a circular area having apparent radius φ(0). In Fig. 4(a) this is represented by the solid line. The light coming from the encircled area will not be able to reach the observer, since this would require an even stronger deviation than that corresponding to h=0.

Observing Fig. 4(a), let's suppose now that L represents the position of the Sun limb during the egress of Venus. The disk of the planet, as seen from the Earth, will partially project (dashed line) outside the Sun disk (f>0). At position L, however, the circle representing the light source for the refracted light will still be entirely inside the solar disk. As a consequence, the fraction of planetary limb being seen against the sky will be surrounded by a bright halo. Later, when the solar limb will be in L', the portion of limb farthest from the Sun will appear dark since its "source" region will be outside the Sun disk.

This situation is seen from the Earth observer as in Fig. 5(a). The solid circle represents the disk of Venus, while the dashed one is the source region. The limb segment outside the Sun disk and luminescent due to the aureola can be obtained by simple geometrical construction, by considering the projection on the limb itself, across the planet centre, of the intersection between the Sun limb and the source circle.

However, this is not the only possible configuration. In fact, if the refraction was stronger, the deviation ω(0) could be higher. In that case φ_v e φ could become negative, as in Fig. 4(b). To derive the aspect of the planet (Fig. 5(b)) the geometrical construction is now slightly more complex: it is always necessary to consider the intersection between the Sun limb and the source circle, but the projection is made on the side opposite to the planet centre, as it can be deduced in the Fig. 5(b).

The result is very different in the two situations. In the first one the aureola breaks at small values of f, then gradually reduces and disappears, with the source limit circle rapidly leaving the Sun.

In the second case, the source region is farther away the solar limb, and the aureola persists as a complete arc until f=0.5. For large values of f, the bright arc is detached

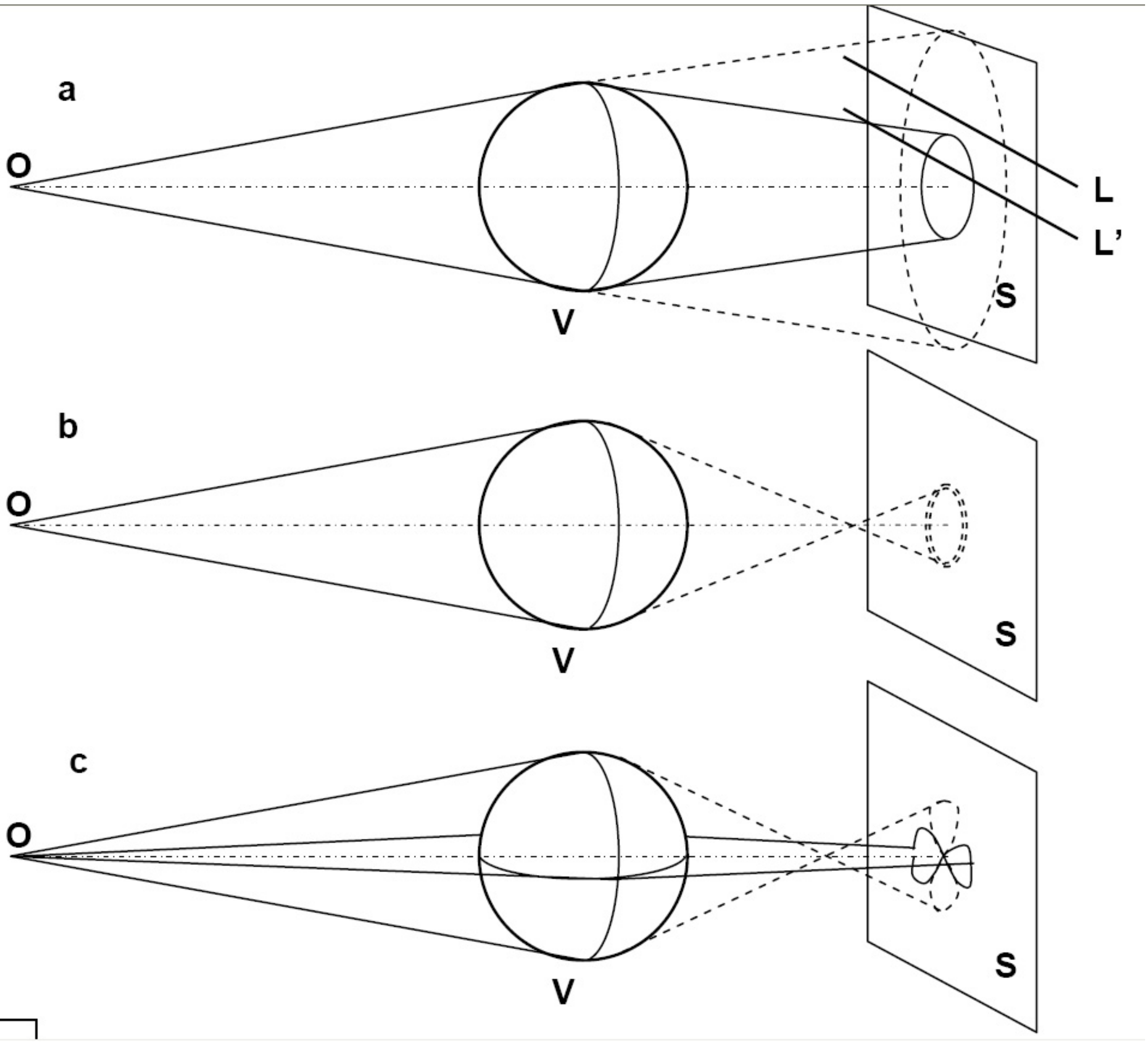

Figure 4 – The projection of a refracted solar region (ellipse on the photosphere S) toward the observer in O, for small (a) and large (b) deviations. In (c) the refraction index varies: strong as in (b) close to the poles, and smaller, as in (a) at the equatorial regions, with a transition at intermediate latitudes.

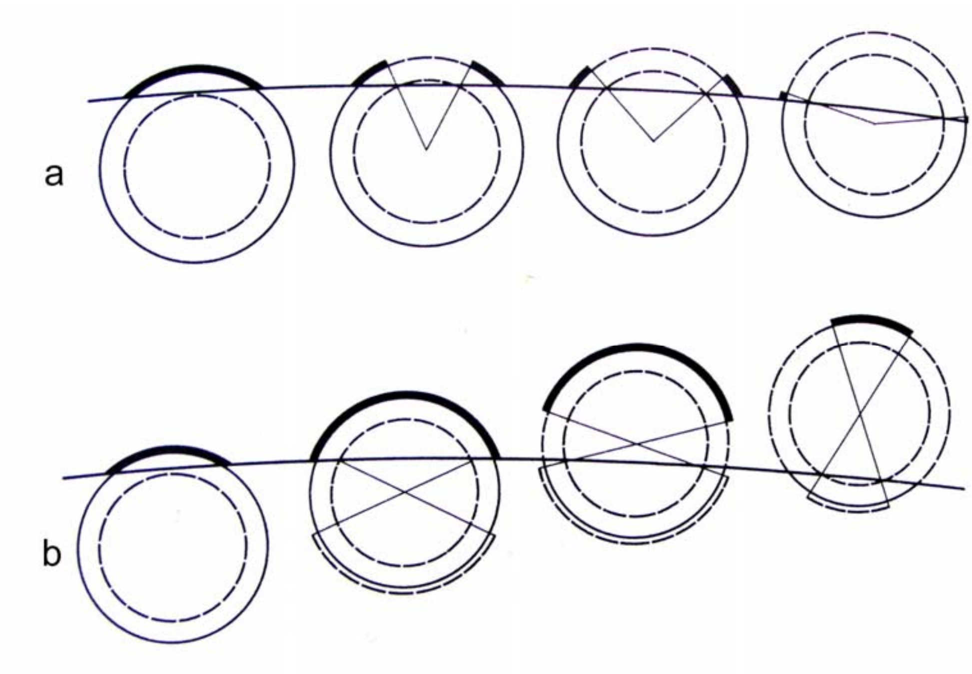

Figure 5 – Aspect of the aureola at different phases during the transit ingress and egress, for small (a) or high refraction indexes (b). The dashed circle correspond to the source region (when the refraction index is constant along the planet limb) also drawn in Fig. 4.

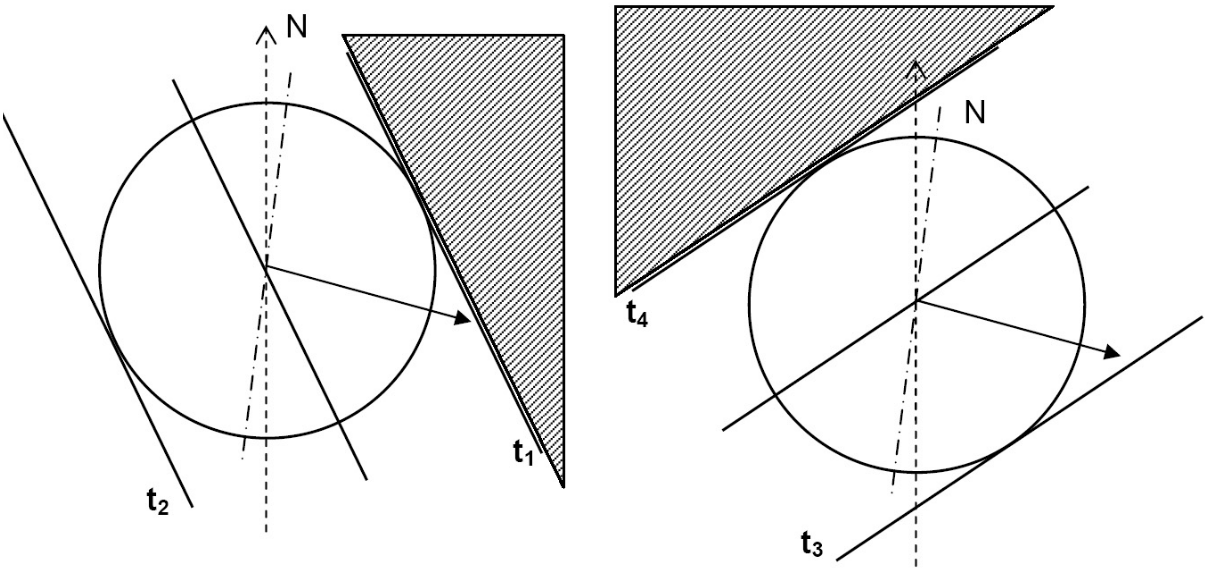

Figure 6 – Orientation of Venus disk at the ingress (at left) and egress (at right) of the 2004 transit. The celestial North is up (dashed vertical arrow). The dash-dot line indicates the position of Venus rotation axis. The dashed region corresponds to the photosphere when the planet is externally tangent. The position of the Sun limb at main contacts and at f=0.5 is indicated. The arrow toward the right represents the apparent motion of Venus relatively to the Sun.

from the solar limb at both ends, and gradually reduces its extension.

Interpretation of the observations

The limit value of the refraction angle separating the two situations (a) and (b) corresponds to the sum of the angular semi-diameters of Venus as seen from the Earth and the Sun, $\omega = \pi_v + \psi_v = 43$ arcsecs. The amplitude of this angle is extremely small, and it is reasonable that, if the real ray deviation is close to it, the transition between the two domains can be easily crossed.

This is better realized going back to examine the historical records: situation (a) certainly explains part of the observations, but it is necessary to invoke a larger value of the refraction angle (case b) to account for the presence of bright segments close to the polar regions when $f>0.5$ (Tab. 1). It is also conceivable that ω, in general, can vary along the planet limb. In this case the circular approximation for the limit of the source region is no longer valid.

If ω crosses in specific regions of the limb the critical value of 43 arcsecs, then two limiting curves exist, one related to positive values of φ e φ_v, the other to negative ones. Both curves passes through the centre, the transition point at which $\varphi = \varphi_v = 0$. This “mixed” case is illustrated in Fig. 4(c).

The observations tentatively suggest that the complete aureola is observable at $f<0.5$. Later, it “opens” (Fig. 1, observation B-2 in 1761) and the polar spot becomes visible, up to $f=0.8$ (Fig.2). We can conclude that a value of $\omega(0)$ close to 43” should be associated to low and intermediate latitudes, while it could reach $\omega(0)\sim 90$” close to polar regions. This fact is in agreement with a lower atmospheric temperature close to the poles.

From the historical point of view, it must be noted that this observations gave further support to the growing evidence, at the beginning of the 60s, of a rotation of Venus not synchronized with its revolution. In fact, in a “locked”, synchronous rotation, the planet always faces the Sun with the same hemisphere and any climatic differentiation as a function of latitude can hardly be present.

Taking into account the current knowledge of Venus atmosphere, we can state that the refraction takes place in rarefied layers, and the h=0 level should correspond to a pressure of ~1 mb, at which the scale-height of the atmosphere is 5 km [3]. This thickness, at Venus distance, is extremely small, implying that the refracted image of the Sun does not subtend more than 0.02 arcsecs for the observer on Earth. Nevertheless, its surface brightness is close to that of the Sun photosphere. This is the reason for which it remains visible even when using very dense filters, such as those necessary for solar observations.

The observed thickness of the aureola as observed in the past is thus probably due to the strong daytime turbulence of the image, with observers travelling to sites never tested for seeing quality before. Optical quality of instruments can sometimes have played a role in further dispersing the thin arc [1].

The situation in 2004

The 2004 transit opportunity is particularly interesting from the point of view of the associated twilight phenomena since it is the first occurring in the era of electronic devices and digital techniques applied to astronomy. The event will be observed with instruments meeting a relatively high optical standard, and with a considerable variety of methods: from traditional visual techniques, to film photography, to digital recordings by camescopes, webcams and astronomical CCD cameras.

It is thus reasonable to hope that it will be possible to reveal new details of the formation and disappearance of the aureola. In Fig. 6 the orientation of Venus disk relatively to the Sun limb is given, both close to ingress and egress phases. As it can be noted, in both cases the temperate latitude are tangent to the Sun for f=0 and f=1. At first contact the South Pole of Venus remains projected longer on the sky, while the northern one is already on the Sun disk. The sequence is inverted between third and fourth contact. However, given the low inclination of the polar axis of Venus relatively to the Sun limb, the time interval separating the possible appearance of a polar spot from the formation a complete aureola could be rather limited.

The cusps extension and the elusive ring of light.

When Venus gets close to the inferior conjunction and its disk reduces, due to the large phase angle, to a thin crescent, its thin tips (the cusps) tend to extend well beyond the geometrical prediction for an opaque sphere. The cusps extend, becoming extremely thin, and approaching to each other along the dark side of the planet limb. The effect is particularly impressive for solar elongations <15°.

It was noted, for the first time, by Johann H. Schroeter from his private observatory at Lilienthal, in May 1790, observing in full daylight. Three years later, William Herschel reported new observations, and engaged a debate with Schroeter on the measurements and the origin of the peculiar aspect.

In December 1842 Guthrie saw the two cusps reaching each other, and joining to form a complete ring of light. This configuration was later observed by several astronomers and confirmed by photographic measurements at Lowell observatory, in 1938, and by J. Edson of NASA (in the period 1938-1954, 2000 pictures obtained). In 1964 the cusp extension was studied by photography and polarimetry at the 60 cm refractor telescope of Pic du Midi [5].

The pictures secured by Edson (Fig. 7) are particularly interesting and show two main characteristics of the cusp extensions:

- in general they are not symmetric in both extension and surface brightness;
- their colour is neutral, despite some redder patches can appear at times.

The reason for cusp extension can be obviously identified in the terminator displacement relatively to the opaque sphere model. In other words, the region reached by sunlight extends beyond the planet hemisphere.

The first explanation given for this effect, again, invoked atmospheric refraction. The minimal refraction angle corresponding to the complete ring of light would thus be equal to the maximal elongation at which the ring itself is observable.

The measurement of that critical elongation is extremely difficult, due to the proximity of the Sun and the consequent high brightness of the sky background. The instrument setup is not trivial, since Sun light diffusion must be limited. It has also been observed that the surface brightness of cusp extension is more than three orders of magnitude lower than the aureola brightness.

Observing conditions (sky transparency in particular) and instrument aperture can also play a fundamental role.

The measured critical elongation for the complete ring visibility is thus affected by a strong uncertainty, however it has always fallen in the interval between 1.9 and 3.7 degrees, its average being 2.6°. This value corresponds to a refraction angle more than 150 times the one observed during transits. Beside this discrepancy, two strong arguments opposes to the refraction hypothesis. First, as Russell suggested [6], when the cusps meet and form the complete ring, a bright Sun image should form at their meeting point. This image is never observed. Second,

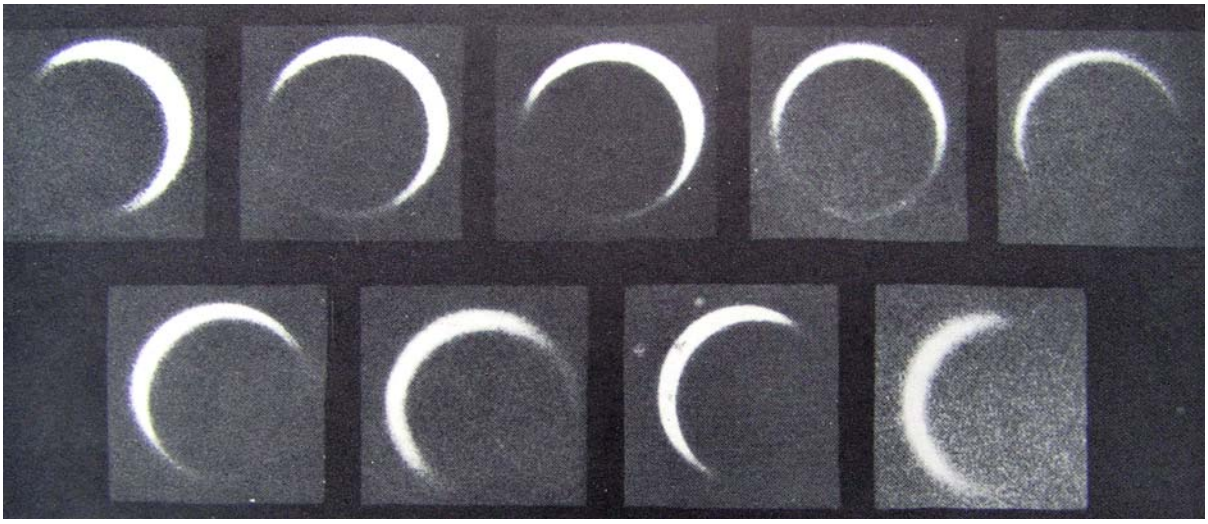

Figure 7 – Photographic images of Venus obtained by Edson using a 15 cm telescope on June 22, 23, 24, 25, 26, 27, 28, 30 and July 1, 1940 (from left to right, up to bottom).

Figure 8 – Edson shielded the Sun by putting a screen on the top of a long pole, sustained and movable thanks to a systems of ropes and pulleys. He observed with a group of students, from Table Mountain, close to the Smithsonian Solar Observatory.

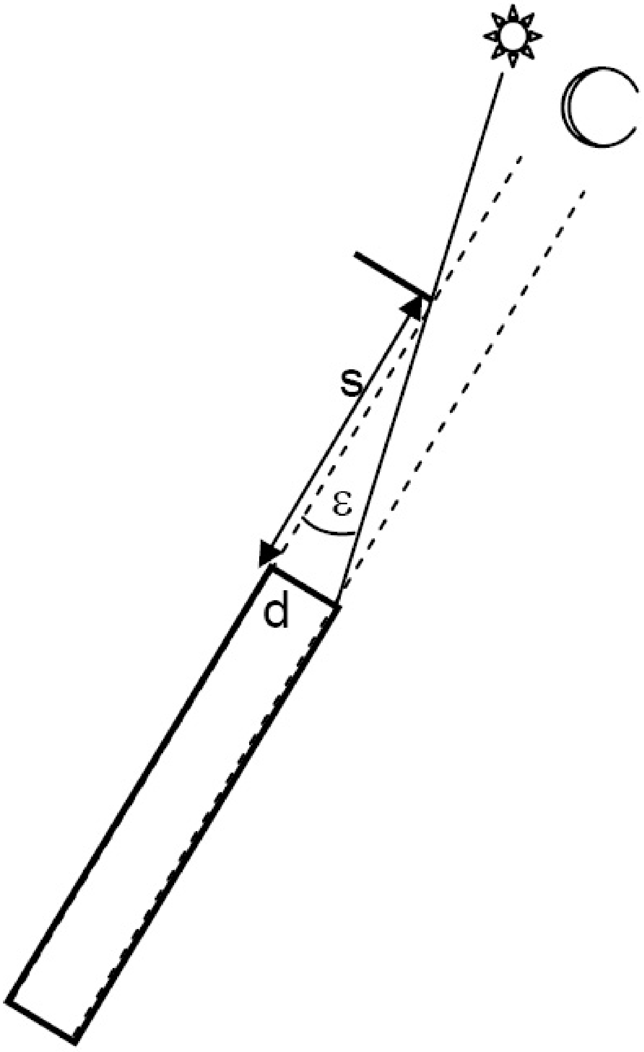

Figure 9 – Simple geometric construction illustrating the necessity of a screen, at distance s from a tube opening of aperture d, when Venus elongation from the Sun limb corresponds to the angle ε.

such a large deviation should correspond to a light path going through hundreds of km of atmosphere, with a consequent reddening of the solar radiation, again never detected.

Russell, in 1899, was the first to give a suggesting that proved correct, invoking light scattering by a diffuse atmospheric layer above the clouds. It can be shown that a layer thickness of 2.5 km is sufficient to explain the terminator displacement in agreement with observations [1], consistently to the estimate obtained by Dollfuss [5]. In more recent times, space probes have shown that the responsible layer contains aerosols.

The irregularities along the cusps testify local variation of scattering properties yielding surface brightness fluctuations of a factor ~5.

Practical suggestions for the observation of the ring of light.

Past experiences have shown that, if the cusp extension is easily observable, the sight of the complete ring requires special methods and cannot be obtained by an occasional observer.

In fact, above all, an extremely close inferior conjunction with the Sun should occur: no more than 3 degrees from the Sun limb and possibly less.

This is obviously not the case with all conjunctions, but it is clear the conditions in the period around the 2004 transit will be particularly favourable. During the transit, the apparent motion of Venus will be about 1.5 degrees/day. The astronomical conditions for the observation of the complete ring will thus be verified from June 6 to 10, 2004.

The positive detection of the ring is the result of favourable observing conditions, especially concerning transparency and lack of diffusion around the Sun.

Furthermore, the instrument – used in general without filters - pointed at ~2 degrees from the Sun, has to be carefully shielded by direct sunlight (Fig. 8), otherwise the diffusion caused by the tube walls or the objective itself can easily prevent any observation. It is thus necessary to build a “sunshield” capable of casting a shadow over the entrance of the instrument during the observation. It can be built using a light but rigid panel, bigger than the aperture, and suspended close to the incoming light path, displaced toward the side exposed to the Sun (Fig. 9).

The distance *s*, in front of the tube, at which the shield should be installed, is a function of the elongation ε of Venus (measured from the Sun limb) and it is given by: $s = d/\tan \varepsilon$, in which *d* is the instrument diameter. If d=10 cm and $\varepsilon=2°$ the formula gives s=286 cm. It is easily seen that the resulting structure (shield plus support) poses serious problems of stability and rigidity to amateur-class instruments. At smaller elongation, the problems rapidly grow. A possible help can come from a reduction of telescope aperture to 5-6 cm. The finder of a long professional refractor can offer the best solution, with the top of the main tube providing an ideal mounting for a sunshield.

Any sort of solution can prove efficient, anyway, provided that the safety of the unprotected eye from an accidental pointing of the Sun is assured. For example, the shadow of a tree or a high building nearby can block sunlight for a few minutes. In 1866 Lyman was particularly lucky, exploiting a passing cloud that hid the Sun!

Anyway, if the ring of Venus is a real astronomical challenge, the cusp extension, visible at more than 10^{o} of elongation, is much less critical to observe and equally rich of interesting features. The observer should pay attention, in particular, to irregularities in surface brightness (spots, segments, interruptions) and measure the extension of both cusps while preserving the correct orientation of Venus disk: in fact, it has been shown that the extension of the two cusps can be different, and they can be accurately measured only if the orientation of the planet image is carefully recorded.

It is also interesting to observe through different coloured filters. Past observations have shown that the extension is larger at small wavelengths (blue-violet). On the other hand, a better contrast with the background sky will be obtained through orange/red filters.

Conclusions

The 2004 inferior conjunction of Venus presents ideal conditions for the observation of twilight phenomena.

Both cusp extension and transit halos are caused by Venus atmosphere, but their origin is different, the first being in agreement with light scattering, the second with refraction. Consequently, the refracted Sun image observed during transits is far brighter, and its surface brightness is comparable to that of the photosphere. For this reason it is observable through the dense filters used during Sun observing.

Due to the small vertical extension of the atmospheric layers associated to those phenomena, both the cusp tips and the aureola have a thickness well below the resolution limit of most Earth-based telescopes, especially considering the limitations due to the average daytime seeing. Turbulence diffuses the light and is probably responsible of both a reduction in surface brightness and the apparent, finite thickness observed in the past. For the same reason, poor transparency and bad seeing can pose severe limitations.

Anyway, the observer should be motivated by the possibility of collecting data that are exceedingly rare in scientific literature.

As J.B. Edson wrote:

"*Of such are the twilight phenomena of Venus. Like some others of Nature's best kept secrets, they lie open to the simplest of access ; unseen because they are unsought.*"[4]

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