N-33561 (NAS 7-100)

MEMORANDUM
RM-3194-JPL
JUNE 1962

VENUS: A Chapter from Issledovaniye fizicheskih uslovii na lunye i planetakh (Investigations of the Physical Conditions of the Moon and Planets). Kharkov, 1952.

N. P. Barabashev

Translated from the Russian
by Douglas Scott and Dolores Mohr

PREPARED FOR:
JET PROPULSION LABORATORY
California Institute of Technology

The RAND Corporation
SANTA MONICA • CALIFORNIA

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This research is supported and monitored by the Jet Propulsion Laboratory, California Institute of Technology under Contract No. N-33561 (NAS 7-100) for the National Aeronautics and Space Administration. This report does not necessarily represent the views of the Jet Propulsion Laboratory or the National Aeronautics and Space Administration.

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PREFACE

The RAND Corporation is conducting a number of studies for the Jet Propulsion Laboratory, California Institute of Technology, on the physical properties of the Moon and the planets. The work is performed under Contract No. N-33561 (NAS 7-100). At the suggestion of Diran Deirmendjian of the RAND Planetary Sciences Department, who also gave editorial assistance, this chapter from a book by N. P. Barabashev was translated for publication under this contract. Barabashev is a leading observational astronomer of the U.S.S.R. Since his study of Venus treats primarily of the optical properties of that planet, this translation is believed to be a timely and useful article for those who will be charged with interpreting the optical data gathered by Venus probes.

SUMMARY

In this chapter N. P. Barabashev summarizes and reviews certain important observational data about Venus, particularly the brightness distribution, albedo, color index and indicatrix of scattering as obtained by Schoenberg, Müller, Danjon, King, Barabashev, and others.

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VENUS

Venus, like Mercury, seems to us sometimes a morning, sometimes an evening star, but is considerably brighter and much more easily observable. Sometimes when the atmosphere is sufficiently clean and clear, one can see Venus with the naked eye even in the daytime, in full sunlight. At its inferior conjunction with the Sun, Venus is less than 40 million kilometers from the Earth. At this time, it has its dark, unilluminated hemisphere turned towards us. Venus' average distance from the Sun is 108 million kilometers. Its orbit is very nearly circular and takes 225 days.

Venus' diameter is 12,600 km. Its mass is 0.818 times that of the Earth, but its density is 0.843 times the Earth's.

At its greatest elongation from the Sun (47° to 48°), Venus shines more brightly than any star. At this time its brilliance exceeds that of the brightest star, Sirius, by almost 13 times.

Observing Venus with a telescope, we become convinced that almost nothing is visible on its surface. Sometimes one can note faint, indefinite spots, which vary in their position on the disk. These are cloud formations.

In 1927, the astronomer Ross photographed Venus, using various light filters on 60- and 100-inch telescopes, and discovered that many dark and light spots were visible only on ultraviolet photographs. According to Ross, the light spots on Venus were clouds, like our cirrus, and the dark spots were breaks in the cloud formations, through which an underlying layer of the atmosphere was visible. This layer is yellowish in color, owing its origin to clouds of dust floating in the lower layers of the planet's atmosphere.

The light spots, distinctly visible in the photographs through an ultraviolet light-filter, are more or less circular, and are most often found near the horns of the planet's crescent.

Ross says that Venus' poles are at the horns. The dark spots — breaks in the clouds — are usually band-shaped, and are distributed near the planet's equator. All these spots are quite variable. They change quickly, alternately appearing, and vanishing. To explain Venus' rotation period, Ross compared seven photographs he took in one hour, and noticed no visible displacement of the spots. From this, it follows that Venus' rotation is considerably slower than our Earth's 24 hours.

Radiometric measurements of Venus showed that the temperature on its sunlit side reaches $+50^{\circ}$ and $+60^{\circ}$, while on the dark side it falls to -23°C. Thus, variations between daytime and nighttime temperatures on Venus are not great. This would indicate that Venus is surrounded by a dense atmospheric layer, and cannot always have the same side turned towards the Sun. Its rotation period is approximately equal to one Earth-month.

As early as 1761 the great Russian scientist M. V. Lomonosov, discovered the existence of a dense atmosphere on Venus, while observing the transit of Venus across the face of the Sun. He noted that as the planet began its transit across the face of the Sun, the solar limb blurred, "whereas before it had been quite distinct and everywhere uniform." When Venus was approaching the other limb of the solar disk, Lomonosov observed "an indistinctness of the solar limb" and a ring of light around the dark face of Venus when it had already passed beyond the Sun's face, about which phenomenon we have already spoken.* From these observations Lomonosov concluded that Venus is "surrounded by a substantial air atmosphere of the

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*Ed: Reference is in earlier chapter.

same kind as (<u>though not greater than</u>) that which encircles Earth." While observing Venus' crescent, one notes that its horns extend far beyond half the circumference, and when the crescent is very narrow, the horns even become a complete ring surrounding the planet's dark face. V. G. Fesenkov and B. Lyot demonstrated that this extension is caused not by refraction in Venus' atmosphere, as some astronomers — including E. Schoenberg — had thought, but by the scattering of light. A measurement of this extension, as made by the author with photographs made at the astronomical observatory of the Kharkov University, completely confirms the conclusions of Fesenkov and Lyot.

The spectrum of Venus has been studied by many astronomers. Their studies showed that the amount of oxygen above the cloud layer cannot exceed 1/1000 of the amount of oxygen in the whole of the Earth's atmosphere. No water vapor was discovered at all.

Studies of Venus using light filters indicate that its atmosphere must consist of two layers. The upper is thin and rarified. The depth of the lower layer is considerably greater. This layer, as we have already said, is supposed to be yellowish in color. In 1932, Adams and Dunham at the Mount Wilson Observatory discovered wide CO_2 bands in Venus' spectrum. It seems that there is a large quantity of CO_2 above the clouds. It corresponds to a 400- to 3200-m column of this gas at Earth's atmospheric pressure. However, it is conceivable that below Venus' cloud layer both oxygen and water vapor exist.

For studying the properties of its atmosphere, E. King's(92) curves of the Venus phases are often given. According to these curves it appears that the phase dependence of Venus' brightness is the same for photovisual and photographic wavelengths.

The photovisual curve is

$$J = -5.20 + 0.01445\alpha + 0.000002257\alpha^3.$$

The photographic curve is

$$J = -4.29 + 0.01445\alpha + 0.000002257\alpha^3.^*$$

Until recently it was thought that Venus' color index was constant and did not change with the phase. We summarize below the determination of several authors:

From the visual observations of G. Muller and the photographic observations of E. King the color index is equal to +0.77, and the photovisual and photographic observations of E. King give +0.91. In 1948 N. P. Barabashev and A. T. Chekirda, by measuring the intensity distribution in Venus' spectrum with an objective prism at the Kharkov observatory, found the value 0.95(93). A. Danjon obtained for Venus' color index +1.00(89). Further observations of Venus' color index are very desirable.

R. Wildt proposed that Venus' clouds are composed not of water droplets, but of crystals of formaldehyde, having the chemical composition of CO_2 and water vapor ($CO_2 + H_2O = CH_2O + O_2$).** However, in the formation of formaldehyde, free oxygen must be liberated. That the spectroscope does not disclose it, in this case, is incomprehensible. Wildt thinks that this free oxygen must somehow leave Venus' atmosphere. The formation of formaldehyde proceeds until sufficient water is stored up. Pure gaseous formaldehyde is colorless, but large admixtures of water begin the formation of heavy, shining clouds in it. These clouds, floating in the atmosphere, conceal the surface from us.

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*Ed: Where α is the phase angle.

**An obvious error in the text has been corrected.

In our opinion, Wildt's theory about formaldehyde is entirely artificial, and does not explain:

1. Why such a sensitive method as spectral analysis does not disclose the lines of such a gas in Venus' spectrum;
2. Why are there no traces, in the planet's atmosphere, of oxygen, with which formaldehyde is formed; and
3. Why there is not the least trace of water vapor, which also plays a role in the formation of formaldehyde.

These questions are not explained by the artificial hypotheses of some scientists.

We should also mention the important polarimetric observations of B. Lyot, which testify to the presence of water vapor on Venus(16). Lyot (1922 - 1924), with his sensitive polarimeter, noticed a clearly pronounced variation in light polarization on Venus and established the rotation of a plane of polarization. According to his observations, the polarization equals zero at the time of superior conjunction ($\alpha = 0$). Its greatest value, equal to 4 per cent, is observable at the time of quadrature ($\alpha = 90^\circ, 270^\circ$). The parts of Venus' disk lying near the terminator, where the light incidence angle is nearly 90°, always show a larger polarization than the brightly illuminated absolute edge of the face. Lyot finds that the polarization curve is quite similar to the polarization of a cloud of fine water droplets. These observations quite unambiguously contradict the opinions of the investigators cited above.

Several authors have tried to obtain a curve of Venus' brightness, taking into account the reflection from the surface and the dispersion of light in the atmosphere. Here they proceed from an assumption about the existence of refraction in Venus' atmosphere, on the basis of V. Raabe's observations of the crescent horns' extension.

One should note, however, that any conclusion about the presence of refraction, based on the horns' extension, is highly suspect. We have already said that the phenomenon of extension of the horns is caused not by refraction, as was earlier supposed, but by light scattering in the lower layers of the atmosphere. V. G. Fesenkov came to the same conclusion in his paper, "Concerning the ashen light and refraction in Venus' atmosphere,"(95) by determining the ratio of Venus' surface brightness near the terminator to the atmospheric brightness caused by scattering. For an atmosphere similar to the Earth's, at a phase angle equal to 90° and in the central part of the planet, this ratio proved to be 0.03.

Much later, F. Link obtained for this ratio a value of 0.06. He used an analogous calculation, but with different assumptions concerning the atmospheric composition (believing Venus' atmosphere to consist of CO_2). In that paper, furthermore, extrapolating the dependence of Venus' brightness on the phase angle to an angle equaling 180°, he obtained for the density gradient a value so large (2×10^{-4} cm^{-1}) that it forced him to believe the scattering layer to be non-gaseous. He calculated the altitude of this layer as 2.4 km, by observing the horns' extension.(96) We must also note the absence of a refraction image of the Sun at the moment of Venus' inferior conjunction, which Russel indicated to be one of the proofs that the extension is caused not by refraction, but by light scattering in the lower layers of the atmosphere.(97)

We may conclude that if our Earth were constantly covered with clouds having an albedo of 0.55, then its phase curve would be the same as that observed for Venus. The phase curve for a cloud albedo of 0.59 and absolute atmospheric transparency p = 1.00 (i.e., a complete absence of atmosphere above the clouds) does not satisfy the observations.

T. Banakhevich(98) proves that a theoretical phase curve for Venus at large phase angles would correspond very well with the observed curve if we assume that the main source of the radiation reaching the Earth from Venus is atmospheric and that the light reflected from the surface does not exert a marked influence. The formulas applied by Banakhevich are variables of the formulas of Lambert photometry, giving the surface brightness of diffuse or scattered radiation in the sky, as observed from inside or outside the atmosphere.

TABLE 6

The Indicatrices of Scattering for
the Atmosphere of the Earth and Venus

γ	0°	15	30	45	60	75	90	105	120	135	150	165	180°
Earth	4.60	3.30	1.90	1.30	0.94	0.75	0.64	0.65	0.72	0.85	1.03	1.14	1.20
Venus	7.20	6.00	2.70	1.50	1.00	0.67	0.51	0.40	0.35	0.41	0.56	0.65	0.70

Most interesting results were obtained not long ago by V. V. Sharonov. While investigating crepuscular phenomena on Venus from photographs taken on a 15-inch Pulkovo refractor, he found that their intensity exceeded the intensity of crepuscular phenomena on the Earth by a factor of 3 to 4. According to Sharonov's investigations, this attests to an extent and mass of atmosphere on Venus 3 to 4 times greater than on Earth.

Professor Sharonov also noted, quite accurately, that it is possible to determine the horizontal refraction in Venus' atmosphere only from an observation of Venus' transit across the face of the Sun. Using Lomonosov's well-known observations of this phenomenon, he obtained for horizontal refraction the value 20."(124) An apparent contradiction of this value is the horns' extension near the inferior conjunction, approaching 5 to 6° (against a dark background). Sharonov explains this discrepancy by introducing a special hypothesis about the structure of Venus' atmosphere. To wit: he believes that the visible surface of Venus is a thin, semi-transparent cloud cover, separated from the planet's solid surface or from opaque clouds by a layer of transparent gas having a significant geometric depth. The optical depth of the cloud cover must be such that direct solar radiation entering at a tangent is totally extinguished, while scattered light passes in sufficient quantity. Under these conditions one can see only an image of the Sun refracted in a comparatively thin gaseous layer lying above a stratum of aerosol, whereas the diffused light can extend rather far beyond the terminator.(125)

Very interesting is the attempt of V. V. Sobolev(78) to deduce a law of light scattering in Venus' atmosphere as a function of the phase angle, with a consideration of higher orders of light scattering. Sobolev considered only the first two terms in the expansion of the indicatrix of scattering in a series of Legendre polynomials. He thinks that Venus' atmosphere has an infinitely large optical thickness; consequently, the reflection of light from Venus' surface does not exert a marked influence on the phase curve, which primarily depends on light scattered in the planet's atmosphere.

Sobolev goes further: the albedo of the medium equals 0.6; along with scattering there is also a genuine absorption. For a spherical indicatrix of scattering, the ratio of the scattering coefficient to the coefficient of light attenuation equals 0.95. Since Venus' atmosphere apparently possesses a very elongated scattering indicatrix, this ratio is even closer to unity. On this basis, Sobolev, in deriving the necessary formulae, neglects the value $(1 - x)$ $(\lambda = 0.95)$. Using a curve of stellar magnitudes of Venus which is a function of the phase angle, and knowing the stellar magnitude of the Sun, he finds Venus' scattering indicatrix. This indicatrix is very strongly elongated and resembles that obtained on the basis of Mie's theory. It is far more elongated than the Earth's. Sobolev asserts that this testifies to a scattering of light by large particles; i.e., it indicates once again atmospheric dust and the insignificance of molecular scattering of light in Venus' atmosphere.

A table is reproduced below, which gives the scattering indicatrices of the Earth and of Venus, as published in the transactions of the Jubilee Scientific Session of the Leningrad State University.(99) Here γ is the angle between incident and scattered solar rays. It follows from comparison of these indicatrices that Venus' atmosphere must be a great deal dustier than the Earth's atmosphere.

V. Ezersky(100) obtained some data about the properties of Venus' atmosphere by comparing the observations of N. P. Barabashev(101) with the probable distribution of brightness over the face of the Earth as it would be seen by an observer above the Earth. In order to determine the latter, he used observations by Barabashev, V. A. Fedorets, and A. T. Chekirda(102) of a change in luminescence produced by direct and scattered solar light for a horizontal area, as a function of the altitude of the Sun; he also used the same authors' observations of the brightness distribution about the celestial sphere. All these values were determined on the same scale. These observations, made sufficiently accurate with the aid of a selenium photocell, made it possible to obtain:

1. The coefficient of atmospheric transparency for green wavelengths;
2. The dependence of horizontal-area illumination by direct and scattered solar light on the altitude of the Sun;
3. The distribution of brightness in the Sun's vertical for various positions of the Sun;
4. The indicatrix of scattering for the terrestrial atmosphere.

From these, Ezersky obtained the probable distribution of brightness over the face of the Earth, assuming that the solid surface reflects light according to Lambert's law. The following table compares the distribution of brightness over the face of Venus $\alpha = 59.4^{\circ}$ (yellow filter) with that calculated for the Earth along the same equator of intensity and albedo $A = 0.03$.

TABLE 7

The Distribution of Brightness Over the Face of Venus

	a	b	c	d	a'	d'	e'	b'
i	80°	75	70	65	60	55	50	45°
ϵ	20°	15	10	5	0	5	10	15°
Earth . . .	0.487	0.611	0.718	0.843	1.000	1.114	1.282	1.455
Venus . . .	--	--	0.722	0.842	1.000	1.150	1.298	1.420

The agreement of the above distributions of brightness may be explained, beginning with two assumptions. First, Venus' atmosphere resembles Earth's in its optical qualities, while its surface albedo is small (on the order of 0.03). Second, the optical thickness of Venus' atmosphere is quite high, as is its surface albedo; this is also acceptable for the observed distribution of brightness.

Using a visual photometer and a series of light filters, E. Schoenberg(103) determined the distribution of brightness over Venus' face for various phase angles. Having worked out these observations according to his formula, considering both the surface reflection of light and the scattering in the planet's atmosphere, and assuming that Venus' surface reflects light according to Lambert's law (which by the way is far from certain), he obtained the data cited in the table immediately below, in which A is the albedo, C is the coefficient of light attenuation, $\lambda = \frac{c}{C}$ is the ratio of the scattering coefficient to the attenuation coefficient, and P is the transparency coefficient.

TABLE 8

The Albedo of Venus' Surface, with the Attenuation, Scattering, and Transparency Coefficients for its Atmosphere, According to Schoenberg

Filter	A	C	λ	P
Red	0.235	0.136	0.904	0.85
Yellow	0.195	0.177	0.894	0.84
Blue.	0.256	0.653	0.982	0.52

Having calculated from these data the refraction coefficient for Venus' atmosphere, Schoenberg found that it must consist of a mixture of CO_2 and hydrogen. Note that he used the extension of Venus' horns to determine the refraction, and, from it, the refraction coefficient μ. Since the horn extension is explainable not by refraction, but by light scattering, Schoenberg's method for deriving Avogadro's number and the atmosphere's chemical composition is vulnerable.

Barabashev,(101) from his photographic observations through light filters, and by applying the same formulas of Schoenberg for Lambert's law, found the most reliable values for A, C, and λ, as cited in Table 9.

TABLE 9

The Surface Albedo with the Attenuation
and Absorption Coefficients of Venus' Atmosphere
According to Barabashev

Filter	A	C	λ
Red	0.63	0.65	0.25
Yellow	0.63	0.65	0.65
Blue	0.63	0.15	0.59
Blue	0.26	0.65	0.54

Comparing this table with the preceding, we see that Schoenberg's values only agree with Barabashev's second combination of values with the blue filter (excepting λ, for which the difference amounts to 45%). We should remember that Schoenberg's observations were visual, and that he measured only four points on the face of Venus, whereas Barabashev analyzed his photographs on a recording micrometer, and could therefore obtain the brightnesses of a considerably larger number of points on the planet's face(101). Clearly, Barabashev's results deserve greater confidence than Schoenberg's.

Table 10 compares Schoenberg's visual observations with Barabashev's photographic ones for three light-filters (red, yellow, and blue). Taken for comparison are the closest possible phases. Interpolating from Barabashev's observations, we obtain the corresponding brightnesses measured by Schoenberg, i.e., points with the same i and ϵ.

TABLE 10

The Distribution of Brightness on the Face of Venus
According to Schoenberg and Barabashev

	Red Filter											
α_S		76.4°			92.8			104.6			125.8	
α_B		77.2			90.8			98.3			128.9	
i	53.9°	32.5	72.1	61.3	43.3	76.1	65.8	50.1	78.5	73.4	62.1	82.3
ϵ	22.3	43.7	4.1	31.7	49.7	16.8	38.6	54.3	25.9	52.4	63.7	43.5
I_S	0.87	1.13	0.45	0.89	0.96	0.42	0.87	1.12	0.5	0.76	1.13	0.22
I_B	0.87	0.99	0.33	0.89	1.02	0.44	0.87	1.00	0.54	0.76	0.98	0.64

TABLE 10

The Distribution of Brightness on the Face of Venus According to Schoenberg and Barabashev

(cont.)

Yellow Filter

α_S		81.3°			98.8			97.6			122.1	
α_B		77.2			90.8			98.3			128.9	
i	56.2	35.9	73.5	61.3	43.5	76.1	63.0	45.9	77.1	72.2	60.1	81.7
ϵ	25.0	45.3	7.7	31.7	49.7	16.8	34.4	51.5	20.3	49.9	62.0	40.4
I_S	0.67	0.69	0.32	0.72	0.89	0.39	0.80	0.94	0.42	0.71	1.10	0.44
I_B	0.67	1.00	0.32	0.72	1.02	0.41	0.80	0.99	0.27	0.71	1.07	---

Green Filter

α_S		76.4°			92.8			125.8	
α_B		77.2			90.8			128.9	
i	53.9	32.5	72.1	61.3	43.3	76.1	73.4	62.2	82.3
ϵ	22.3	43.7	4.1	31.7	49.7	16.8	52.5	63.7	43.6
I_S	0.87	0.86	0.42	0.82	0.79	0.44	0.86	0.96	0.55
I_B	0.87	1.00	0.33	0.82	1.13	0.56	0.86	1.10	0.63

Table 10 clearly shows that Schoenberg's observations often differ slightly from those of Barabashev. We see this with the red light-filter for the phase angles $\alpha = 76.4^{\circ}$, 92.8°, and 104.6°. For a phase angle of 128.9°, the discrepancies are significantly larger. With the yellow light-filter, the greatest discrepancies are noted for phase angles of 81.3° and 97.6°. The discrepancies are explainable apparently by the fact that Schoenberg, in visually determining the longitude of points, could not compute the direction of his photometer towards the points with sufficient accuracy or, more than that, uniformity. Nor can we be sure that the photometer did not move during the observations. The photographic observations of Barabashev do not suffer from these shortcomings.

From Schoenberg's results, we can conclude that Venus' atmosphere is gaseous, that it scatters light according to Rayleigh's law, and that its density is equal to that of the terrestrial atmosphere, since for the yellow filter Schoenberg obtains $\rho = 0.84$, i.e., the same value as G. Müller gave for Earth's atmosphere. Schoenberg's determinations give a small surface albedo, differing from the albedo of clouds. Conversely, if one considers Schoenberg's formulas to be sufficiently accurate, Barabashev's observations indicate that Rayleigh's law (correct for molecular scattering in the absence of aerosols) is inapplicable to Venus, and that Venus' surface albedo is great, comparable to that of clouds. The atmosphere displays a large true absorption, which does not show noticeable selectivity. This is seen from the fact that all values of C, aside from the first combination for the blue light-filter, are the same. If we assume that Venus' cloud layer reflects in accordance with the law

$f(i \cdot \epsilon) = \cos \epsilon$, then we obtain, again, values sharply different from Schoenberg's for A, C, and λ, and again we come to a conclusion about the presence on Venus of a dusty atmosphere, which does not conform to Rayleigh's law.

From the author's observations in 1923(51), we may conclude that the brightness of points on the face of Venus which are located beyond the terminator is still significant. Twilight effects are quite conspicuous in red wavelengths up to 20° below the horizon ($z_\odot = 110^\circ$) past the sunset point — in blue wavelengths up to 15° ($z_\odot = 105^\circ$). This may be seen in Table 11.

TABLE 11

The Brightness of Twilight on Venus

Filter	90°0	92.5	95.0	97.5	100.0	102.5	105.0	107.5	110.0
Red	1.00	0.81	0.78	0.53	0.44	0.39	0.37	0.35	0.31
Green . . .	1.00	0.67	0.47	0.30	0.14	0.06	0.03	—	—

In 1946 there appeared a paper by M. Minaert entitled "Photometric investigations of the homogeneity of Venus' atmosphere."(107) In this paper, Minaert uses the observations of brightness of Venus' face by Schoenberg and Barabashev (noted above) and applies to them Helmholz's reciprocity principle.

Considering the planet to be of spherical shape, and designating by λ_0 the phase angles, and by i and ϵ the light incidence and reflection angles for any selected point P, and by λ the planetocentric length (the angular distance from the visible center of the disk along the equator of intensity), Minaert applies Helmholz's reciprocity principle to points on Venus' equator of intensity. By I is designated the brightness at point P with incidence and reflection angles i and ϵ, and by I' is designated the brightness of point P', symmetrical with P on an arc of the equator of intensity corresponding to phase angle λ (angle AS). If M is the center of AS, then clearly P' is a sort of mirror image of P (Fig. 42). On the basis of the reciprocity principle, Minaert writes the following ratio:

$$\frac{I}{I'} = \frac{\cos i'}{\cos i} = \frac{\cos \epsilon}{\cos i} = \frac{\cos \lambda}{\cos(\lambda - \lambda_o)}$$

since

$$\lambda' = \lambda_o - \lambda, \quad i' = \epsilon = \lambda \quad \text{and} \quad \epsilon' = i = \lambda_o - \lambda = \lambda'$$

and concludes that if the planetary surface, with or without atmosphere, has the same scattering properties in P and P', then the preceding ratio should be satisfied.

Having used Schoenberg's(103) and Barabashev's(101) observations, giving the distribution of brightness on the face of Venus, Minaert arrives at the conclusion that these observations, regardless of the systematic differences existing between them, show without doubt a deviation from Helmholz's reciprocity principle. In Minaert's opinion, these deviations are not due to systematic errors, but indicate that the cloud layer surrounding Venus has a different structure at noon, morning, and evening, if one assumes that the planet has a direct rotation at the same rate as the Earth.

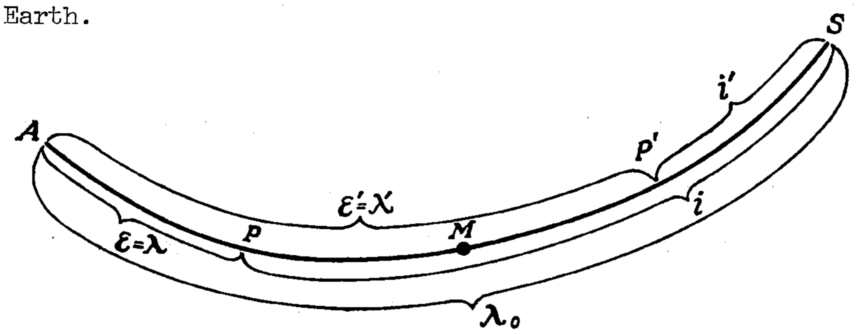

Fig. 42 — Minaert's application of Helmholtz's reciprocity principle

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TABLE 12

The Brightness of Venus and the Earth as a Function of Phase Angle

	Venus			Earth
Observer / Phase	Müller (visual)	Danjon (visual)	King (photographic)	Danjon (visual)
0°	—	-4.84	—	-4.57
15	-4.71	-4.78	-4.07	-4.33
30	-4.70	-4.62	-3.85	-4.09
45	-4.08	-4.38	-3.62	-3.82
60	-3.83	-4.07	-3.38	-3.53
75	-3.54	-3.71	-3.11	-3.18
90	-3.21	-3.30	-2.83	-2.79
105	-2.83	-2.87	-2.51	-2.33
120	-2.39	-2.42	-2.17	-1.82
135	-1.88	-1.97	-1.79	-1.21
150	-1.29	-1.52	-1.36	-0.51
165	-0.62	-1.11	-0.90	+0.29
180	—	-0.70	—	—

In the following table are cited the spherical albedos of Venus and of the Earth obtained from curves of phase functions.

TABLE 13

Table of the Albedo of Venus and the Earth

	Venus			Earth			
Observer / Phase	Müller	Danjon	King	Barabashev	Öpik	Danjon	Orlova
Visual	0.59	0.73	—	0.43	—	0.39	0.42
Photographic	—	—	0.85	—	0.63	—	—

The magnitude of Venus' spherical albedo in photographic range (0.60) was calculated on the assumption that Venus' color-index is a constant value,(21) not dependant upon phase angle and almost equal to the Sun's color index. This assumption also led to an equality in Venus' spherical albedo for visual and photographic wavelengths. At the same time, a comparison of photographic with visual observations of Venus' brightness (as a function of the phase angle) allowed us to discover a systematic dependance of Venus' color-index upon the phase angle. This dependency is presented in Table 14.

TABLE 14

Change in Venus' Color Index with the Phase

α	0°	15	30	45	60	75	90	105	120	135	150	165	180
K-D	+0.55	0.70	0.77	0.76	0.69	0.59	0.47	0.35	0.25	0.18	0.16	+0.21	—
K-M	+0.42	0.63	0.85	0.46	0.45	0.42	0.38	0.32	0.22	0.09	+0.07	-0.28	—

In this table are cited two series of Venus' color-indices. The first was obtained by comparing Danjon's visual observations with King's photographic, the second by similarly comparing Müller's visual data with King's photographic data. Both series show the identical trend of changes in the color-indices.

If King's and Müller's observations are realistic, it follows from this table that Venus' color-index changes insignificantly for phase angles in the interval from 0° to 75°; this apparently convinced earlier investigators of its constancy. For phase angles in the interval 75-165°, the color-index lessens notably, and for the second series even becomes negative at an angle of 165°. In other words, from a comparison of King's photographic observations with Danjon's and Müller's visual ones, it follows that with increase in the phase angle, the color of Venus changes, becoming gradually less yellow. This is probably connected with a noticeable increase in molecular scattering with increasing phase angle, and also with several other physical processes (due to a change in the composition of the scattering particles) dependent on the planet's rotation. Special observations now being performed at the Kharkov astronomical observatory for empirically verifying these phenomena are already giving positive results.

In the following table are introduced six indicatrices of scattering for the atmospheres of Venus and the Earth.

TABLE 15

Indicatrices of Scattering for the Atmospheres of Venus and the Earth

	Venus		Earth			
γ	1	2	3	4	5	6
0°	(7.20)	—	—	—	4.60	—
15	(6.00)	11.23	2.85	2.34	3.30	3.66
30	2.70	3.31	2.03	1.79	1.90	1.09
45	1.50	1.19	1.43	1.41	1.30	0.65
60	1.00	0.26	1.07	1.13	0.94	0.52
75	0.67	0.02	0.85	0.93	0.75	0.51
90	0.51	0.00	0.73	0.77	0.64	0.66
105	0.40	0.05	0.65	0.73	0.65	0.83
120	0.35	0.29	0.73	0.83	0.72	1.03
135	0.41	0.70	0.73	0.93	0.85	1.26
150	0.56	1.10	0.73	1.00	1.03	1.52
165	0.65	1.38	0.73	1.04	1.14	1.85
180	(0.70)	1.51	—	—	1.20	2.36

The first indicatrix for Venus was derived by Sobolev(78) from a theory he constructed for light scattering in atmospheres possessing a high optical density, and from Müller's visual observations. (The figures in brackets, as Sobolev indicates, are the results of small extrapolations.) Sobolev obtained the value $X_1 = 1.8$ and $\lambda = 0.989$.

The second column of the table gives the indicatrix for Venus that we obtained on the basis of Sobolev's same theory and Danjon's visual observations.(89) In this case $X_1 = 1.7$ and $\lambda = 0.995$.

In the third column is the indicatrix for the Earth's atmosphere, as derived by V. G. Fesenkov(105) from his observations and from a theory taking into account only scattering of the first order. Fesenkov's data, for easy comparison are interpolated for the same phase angles and normalized according to the condition

$$\int_0^{\pi} X(\gamma) \sin\gamma \, d\gamma = 2.$$

In the fourth column is the indicatrix V. Ezersky obtained (by Fesenkov's method) from photoelectric observations of the brightness of the sky; the observations were made by Barabashev, Chekirda and V. A. Fedorets at the Kharkov astronomical observatory.

The fifth column contains the indicatrix for the Earth's atmosphere, as obtained by Sobolev from his theory of light scattering in atmospheres possessing a low optical density and from observations of the distribution of brightness throughout the sky.(99)

Finally, in the sixth column is the indicatrix for the Earth's atmosphere, as we calculated it from A. Danjon's observations of the ashen light,(104) using the theory Sobolev used to obtain Venus' indicatrix. This result cannot be considered reliable, since Sobolev's theory is inapplicable to the Earth's atmosphere; nevertheless, it is very interesting as the first attempt to obtain an integral scattering indicatrix for the Earth's atmosphere.

Further, in Fig. 43, all indicatrices mentioned above appear in the same order. From Table 15 and Fig. 43 we conclude that Venus' indicatrices, obtained from Müller's and Danjon's observations, have in general the same character -- they are strongly elongated along the direction of the incident radiation, with the second more extended than the first (except that it has a minimum equal to zero at $\gamma = 90^\circ$; according to Sobolev's data, the minimum does not drop to zero and occurs at $\gamma = 120^\circ$).

An attempt to determine in the same way the scattering indicatrix for Venus' atmosphere from King's photographic observations did not lead to positive results, since negative values were obtained for several angles (around 90°)--which is not physically possible. At present it is unclear where the origin of this phenomenon lies -- either King's observations are insufficiently clear, or in this instance the application of the theory with other initial data is necessary.

One should note that Venus' brightness curve, obtained by Danjon from eleven-year-old observations including 30,000 evaluations of brightnesses and phase angles from 0.9° to 170.7°, are undoubtedly more reliable than the Müller curve.

The indicatrix of scattering which we obtained for Venus' atmosphere is very similar to the one of large particles, as calculated by Shuleykin(73) for $\frac{2\pi\rho}{\lambda} = 9$, where ρ is the radius of the scattering particle, and λ is the wavelength. For this indicatrix, as for ours, the minimum occurs at 90° and is quite pronounced. Shuleykin shows in this study that, with increasing ρ, the quantity of energy scattered in the backward direction gradually decreases, asymptotically approaching the fixed value 0.084.

Figure 44 gives an indicatrix we obtained for Venus and one Shuleykin

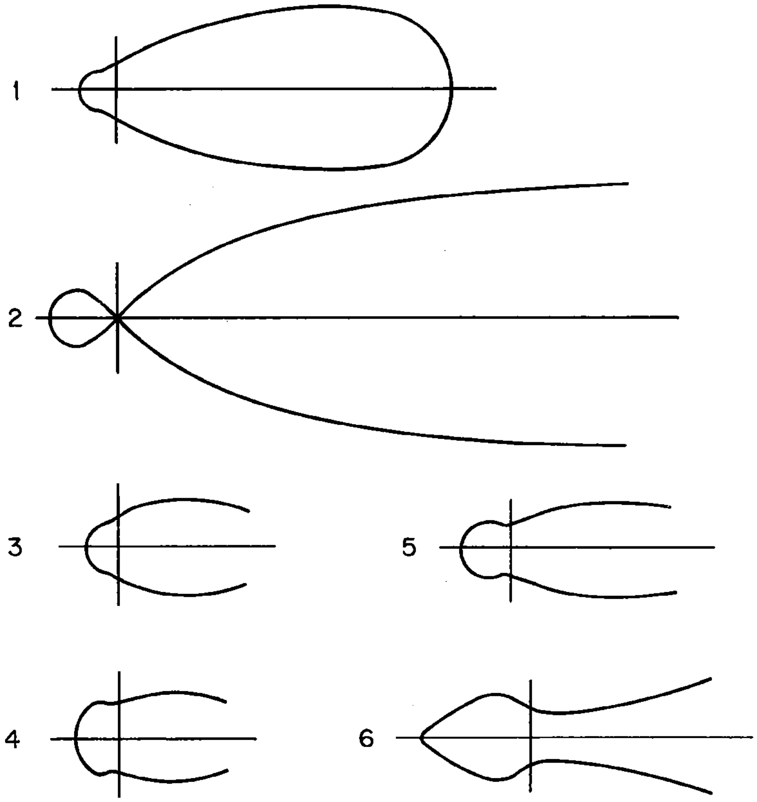

Fig. 43 — Scattering indicatrices derived by Sobolev and Barabashev (for Venus) and Fesenkov, Ezersky, Sobolev, and Barabashev (for Earth)

made it possible to note an interesting characteristic in those parts of the planet's face near the limb which, assuming Venus rotates around its axis in the same direction as the Earth, would be its morning side. In these parts of the face, there was observed a close agreement between the theoretical curves and those observed in blue light, though this agreement disappears in the parts near the terminator.

For red radiation an opposite picture was obtained -- on the average, they give a closer agreement with the theoretical curves near the terminator (the evening side) and a significant divergence in the parts near the limb (the morning side).

Apparently, this peculiarity is explained by a change in the optical properties of the atmosphere with a change in the Sun's altitude, and in particular with a change in the dustiness of Venus' atmosphere. This assumption closely agrees with Minaert's opinion, expressed earlier, concerning the inhomogeneity of Venus' atmosphere.(107)

A second peculiarity is that the brightness maximum for red and yellow wavelengths corresponds to those parts of the planet for which the incidence and reflection angles are almost exactly equal, and lie on either side of the normal. This phenomenon may be explained by the influence of surface reflection, which can influence the brightness distribution over the planet's disc precisely in red and yellow, since the atmosphere is more transparent to these wavelengths than to blue. Regarding the reflecting surface, it is proper to assume that it possesses some specular properties.

Proceeding from the above, one may compare the observed data with the theoretical data calculated for new optical characteristics (i.e., $X_1 = 1.7$ and $\lambda = 0.995$) and for the corresponding indicatrix of scattering. This comparison is introduced in the curves on Fig. 45. Each graph presents the observed curves (red, yellow, and blue light-filters) and the corresponding theoretical curve, where for the unit of brightness we used the brightness of a part for which $i = \epsilon$. Here the incident and reflected light are on different sides of the surface normal.

The graphs in Fig. 45 confirm the peculiarities noted earlier in the tables. In effect, therefore, we can preserve the earlier assumptions about the changing optical characteristics of Venus' atmosphere in the course of a day. The calculation of these changes, however, must await a fuller series of photometric observations of Venus and a further development of theoretical investigations. These data will help clear up the problem of Venus' rotation period.

Such, at present, is our information concerning the physical conditions on Venus.

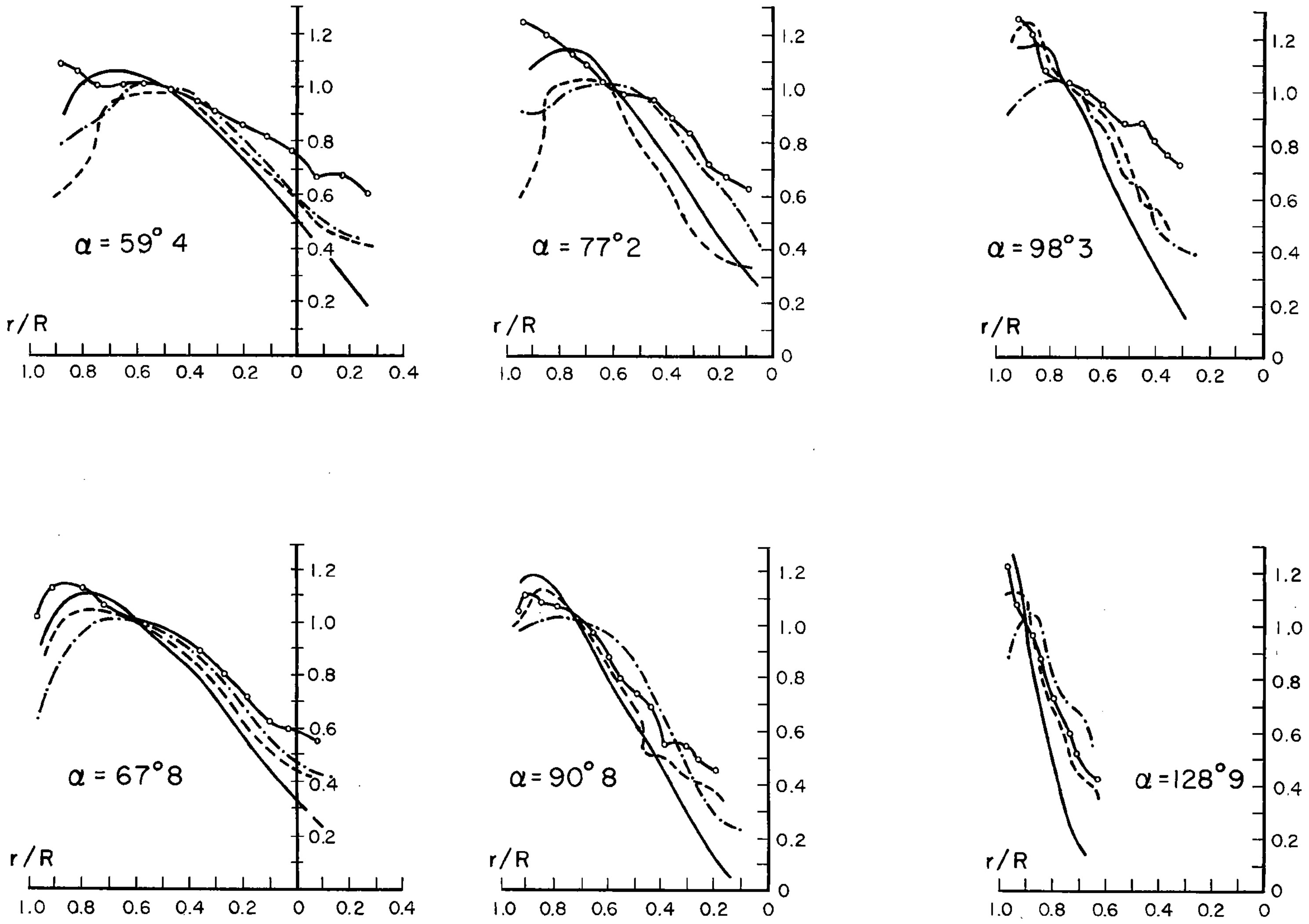

Fig. 45—Brightness distribution curves for Venus' disk

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