ELECTROPHOTOMETRIC SECTIONS OF THE DISK OF MARS IN PORTIONS OF THE SPECTRAL INTERVAL 355—600 nm

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ABSTRACT: Electrophotometric sections of images of Mars and some stars at not too great an angular distance from the planet were obtained with the 70-cm reflector at the Main Astronomical Observatory of the USSR in 1965. The published material is the experimental part of an investigation of the correction to the distribution of brightness along the disk of Mars with account taken of the effect of distorting factors in the terrestrial atmosphere.

In determinations of the optical parameters of the Martian atmosphere, the observed dependence of the brightness factor on distance from the center of the image is usually used. In addition, the variations in time of the rate of decrease in brightness toward the edge of the planet's disk are taken to be a characteristic of the transparency of the Martian atmosphere. In particular, for long observations this material is used for the study of the seasonal variations of the dustiness of the Martian atmosphere, as well as of the density of the "violet haze." As photometric observations of Mars in September, 1956, (during a dust storm) showed [1], the increase in the content of scattering aerosol particles in the Martian atmosphere, in addition to the washing out of surface contrasts, evoked a marked decrease in the steepness of the decrease in brightness toward the planet's edge. Just so, a decrease in the density of the "violet haze" (so-called clearings in the violet layer), which is detected as an increase in the surface contrasts in the violet rays, ought to bring about a variation in the steepness of the fall in brightness of these rays toward the edge. /18

Thus, a systematic study of the rate of decrease of brightness as the edge of the Martian disk is approached can in principle serve as the basis for monitoring the transparency of the atmosphere of the planet.

All of this is completely obvious, and it is no wonder that for many years astronomer-observers of Mars have made partial use of photometric data for just these ends. The originators of the photometric method of planet study, /19 V. V. Sharonov, N. N. Sytinskaya, N. P. Barabashov, and their students, including the authors of this paper, have proceeded in this way [2-6]. As a result, by comparing the photometric curves of the fall in brightness toward the edge of the Martian disk obtained with light filters for several periods of observation (for several oppositions), we ascertain significant changes in the behavior of the brightness toward the edge of the image and relate these changes to variations in transparency of the atmosphere of Mars. From this point of view, for example, in 1958 the atmosphere of Mars was very dusty [7], whereas in

1960-61 it was relatively clean (observations in red light) [8]. The first of these periods was distinguished by relatively low contrasts on Mars and a low steepness of darkening toward the edge. Thus, as was shown in [9], in 1958 the optical thickness of the Martian atmosphere in red light should be several times greater than in 1960-61.

The above discussion indicates that from photometric observations it is possible to obtain valuable information both about the optical density of the Martian atmosphere and about variations in its transparency.

There arises, however, the questions of how valid our earlier photometric data are, in particular the data on the variation of brightness out to the edge of the planet's disk, and to what degree the parameters we obtained for the Martian atmosphere are real. Do we have a right to relate the obtained variations in steepness of the curves of the fall of brightness toward the edge of the disk to changes occurring in the Martian atmosphere? This question is particularly important in connection with the current marked discrepancy in the magnitude of the atmospheric pressure on Mars as found, on the one hand, from the absorption bands of CO_2 [10, 11], and, on the other, from photometric data.

The question of the atmospheric pressure on Mars is one of extreme importance to us at the present time; hence our efforts ought to be directed toward obtaining the most accurate value possible for this important constant.

Let us review the possible errors in the pressure on Mars as determined by spectrophotometric means and point out a number of sources of error in determination of pressure (optical thickness) in photometric investigations.

1. Aerosol effect. This question was studied in [12 and 13], where it is shown that aerosol particles floating in the atmosphere of Mars can lead to a gross overestimate of the pressure. In particular, E.G. Yanovitskiy made a model calculation for the Earth's atmosphere. Using observed data for the coefficient of transparency [14], he obtained a surface pressure of 2300 mb instead of 1013 mb. Although the data he used pertains more to low transparency of the Earth's atmosphere (observations were made at Kharkov), the Martian atmosphere can be still more dusty. Thus, the presence of tiny aerosol particles in the atmosphere can lead to a several-fold increase in the determined magnitude of the pressure. /20

2. Errors in values of the brightness factor. Unfortunately, one cannot cite a single reference that gives estimates of the accuracy of the determination of the brightness factor for the center of Mars' disk. At the same time, just such absolute observations are the most suitable for determination of the optical density of the Martian atmosphere. If we take the average value from a series of oppositions, then we obtain the maximum deviation from the average close to 20% (for $\lambda \approx 430$ nm), which leads to significant errors in the value of the optical density.

3. Assumptions about the orthotropism of the natural surface of Mars. The formulas for the brightness coefficients in the case of an optically thin atmosphere are always derived under the assumption that the underlying surface satisfies Lambert's law. For Mars this assumption is validated by the fact

that the observed behavior in an opposition of the darkening toward the edge in red light, where the effect of the Martian atmosphere is evidently negligibly small, is close to the curve cos i (i is the angle of incidence of the Sun's rays) at least to a distance out from the center of 0.85 R♂. And although in individual periods of observation the curve goes higher than Lambert, observers, as a rule, explain this by an increase in the dustiness of the Martian atmosphere in a given period.

Obviously, the establishment of the true law of brightness distribution for the natural surface of Mars is important and requires special investigations. In observational terms this problem reduces to a much more careful study by photometry of the edge darkening of the image of Mars in the red region of the /21 spectrum. It is difficult to say that the natural surface as a result of these investigations should turn out to be partially reflecting. More likely one can expect departure from orthotropism toward the side of more roughness, which would lead to a decrease in the determined values of the optical density and consequently to a decrease in pressure.

Thus, it must be accepted (without reference to the low pressure on Mars obtained spectrophotometrically) that for the determination of atmospheric pressure on Mars based on photometric data, more accurate observations by a special method are required, taking into account the aforementioned sources of error.

From what has been said, it is clear that the basic photometric characteristic that carries information about the optical density of the atmosphere and the microstructure of the surface of Mars is the brightness distribution over the planet's disk in different spectral regions. Photographic observations of Mars show that the contrast between the same surface details undergoes marked, random variations from day to day. The same day-to-day change occurs in the steepness of the fall of brightness toward the edge on the Martian continents. Both are naturally explained by variations in the transparency of the atmosphere, although the correlation between these effects has not yet been confirmed by photometric investigations.

However, if such a dependence is nevertheless established, there still remains the difficulty in selection of the mechanism causing the marked, random variations in the transparency of the Martian atmosphere [15, 16] with time. It is also obvious that the observed frequent random changes of contrast cannot be due to changes in the intrinsic contrast on the planet's surface.

At the same time, in photometric investigations one is limited, as a rule, by the state of the Earth's atmosphere. Observations for the purpose of surface photometry of a planet are usually carried out with very crude criteria for the suitability of atmospheric conditions for these ends (notably the presence or absence of atmospheric haze). Even the low-frequency component of the turbulent flickering of the image is not always given any attention by the observer, although it is quite obvious that more or less flickering of the image during exposure of a few seconds brings to nothing any attempt to study changes on the planet (of contrast, edge darkening, etc.) Certain errors in the edge-darkening curves can also be introduced by variations in the aerosol content of the Earth's atmosphere in the path of the reflected rays, which in visual observations is manifested by a change in the extent and intensity of the aureole around the planet's image. This aureole, on account of insufficient latitude of the emulsion on the photonegatives under normal density of the planet's image, is usually not printed, whereas in photoelectric scanning of the planet's disk it is observed rather distinctly in the form of "wings" that extend far beyond the ephemeridal edge of the planet. /22

As a result of the simultaneous action of turbulence and scattering of light in the Earth's atmosphere, the energy scattered by the planet in the direction of the observer during scanning of the image with a diaphragm ≈ 0".3 in diameter is registered in the form of the curve shown in Fig. 1 (for observation method see [17 and 18]).

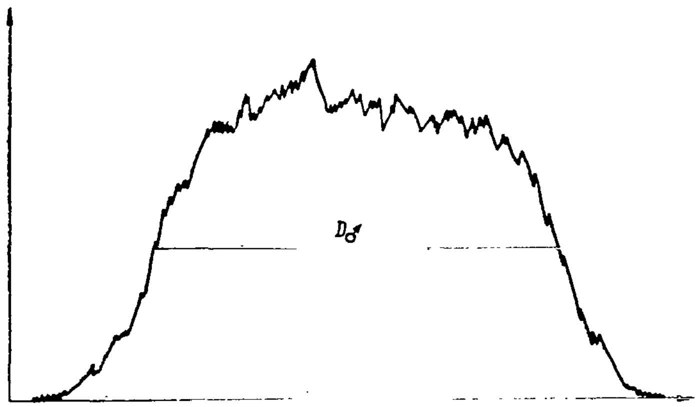


Figure 1. Profile of a Photometric Section of Mars Obtained in 1963, λ_{eff} = 560 nm.

Thus, surface photometry of a planet should be accompanied by certain additional observations which permit monitoring the state of the Earth's atmosphere and serve as a basis for the introduction of corrections to the photometric observations of the planet's disk.

In our opinion, in photometric observations of a planet it is necessary to conduct a parallel scanning of stellar images at a small angular distance from the planet. As Meinel notes [19], the profile of a stellar image essentially depends on the transparency of the Earth's atmosphere and under favorable conditions is not badly approximated by a Gaussian distribution. /23 It is understood that the form of a photometric section of the planet's disk will also vary as a function of the transparency of the Earth's atmosphere. These changes are manifested principally in the magnitude of the wings of the photometric section; however, the measured intensities will also undergo marked variations also within the ephemeridal diameter.

The above pertains to photometric investigations of any extended astronomical object; however, it obviously applies in the first place to investigations of planets with small angular diameter, such as Mars and Venus in certain phases.

The first of our photoelectric sections of Mars was obtained in 1963 [17]. The diaphragm (0".35) was driven by the diurnal motion. Registration was by oscillograph. During the time of observation, the magnitude of turbulence of the image was estimated visually. A typical section profile is shown in Fig. 1. The marked broadening of the observed contour compared to the ephemeridal diameter could not be explained by the disturbing effect of image flickering and finite diaphragm aperture. The corrections obtained turned out to be an order of magnitude smaller than required. To see whether the observed broadening was a result of light scattering in the telescope tube, we made observations on an "artificial planet," which was a uniformly luminous disk placed at a distance of about 300 m from the telescope (angular diameter about 15"). The observed fuzziness of the edge of the artificial planet corresponded to the diaphragm size. Thus, the observed wings on the Mars sections are explainable only by light scattering in the Earth's atmosphere.

During the period of visibility of Mars in 1965, photoelectric observations of Mars and stars by the scanning method were begun. The program provided for obtaining graphs of the brightness distribution on the Mars continents under the most favorable conditions of the Earth's atmosphere for several values of the phase angle in eight portions of the spectral interval 355—600 nm [17].

The observations were made with a 70-cm reflector at the Cassegrain focus (10.5 m). The diaphragm isolated a small circle of diameter 0".3 from the sphere of the sky. The radiation detector was an EMI-9502 photomultiplier. For registration, a PS-10000 counter was used, the output pulse of which closed the contact of a printing chronograph. Thus, the signal intensity was inversely proportional to the time intervals between impressions on the chronograph tape. /24

The duration of scan was chosen such that the time of observation of one point was sufficient for statistical averaging of the signal and amounted to 5 to 10 sec. This rate provided an hour's working time on the average.

During the observation period, the position angle of the rotation axis (< 20°) and the Earth's declination for Mars ($\delta \approx 24°$) were such that during scanning over a diameter the diaphragm moved over the continental regions of the northern hemisphere of the planet.

At the same time observations were made of stars at the same zenith distances as Mars and at nearby azimuths. The observations were programmed such that the stellar image was run through the same filter immediately after Mars. The stars were scanned with a slit of dimentions 0".20 x 100". In addition, control measurements were made with a circular diaphragm (0".3), which showed that the profiles of the stellar images obtained by the two methods did not differ significantly.

The observational data was obtained in March and April with the phase angles of Mars 4° (13/14 March), 11° (23/24 March), 20° (4/5 April), 21° (5/6 April), and 21.5° (6/7 April). However, in treating the data it became clear that the stellar profiles for 4/5 and 5/6 April had a particularly large dispersion of the points, and so this part of the data was not used thereafter.

Figures 2, 3, and 4 show graphs of the distribution of brightness across the diameter of Mars and stellar profiles for three dates. The stellar profiles obtained can be approximately described by a function of the form exp $(-x^2/2\sigma^2)$. As an example, the values of the exponential for corresponding values of σ are plotted as circles on the graphs for 6/7 April. This parameter also determines the observed angular resolution on the planet's disk.

The parameter σ averages 1.5" and varies from day to day depending on the state of the Earth's atmosphere. Unfortunately, the most valuable observations of 13/14 March (an opposition) were obtained under the least favorable atmospheric conditions.

The question arises, how important are the distortions introduced by the Earth's atmosphere into the true intensity distribution over the planet's disk? A similar problem is considered in investigations where the limits of resolution are set by the instrumental contour. /25

Let $F(\vec{t})$ and $f(\vec{r})$ be the observed and actual distribution over the disk. $K(\vec{r} - \vec{t})$ is the distorting function, in our case the stellar profile; then

$$F(\vec{t}) = \iint_{-\infty}^{\infty} f(\vec{r})\, K(\vec{r}-\vec{t})\, dxdy, \tag{1}$$

where

$$|r| = \sqrt{x^2+y^2}.$$

In this general case, to find the true distribution $f(\vec{r})$ it is necessary to measure the values of $F(\vec{t})$ at all points of the observed image, i.e., to obtain parallel sections, which entails considerably difficulty in practice. In addition, it is necessary to have the azimuthal dependence of the stellar profile. The problem is simplified if we neglect the gradient of intensity in the direction perpendicular to the section and the nonsphericity of the distorting function. These assumptions are valid for small effective widths of the stellar profiles and moderate zenith distances. Then Eq. (1) takes the form

$$F(t) = \int_{-\infty}^{\infty} f(x)\, K(x-t)\, dx. \tag{2}$$

With these premises, we constructed the distorted distributions resulting from the action of the function $\exp(-x^2/2\sigma^2)$ for σ = 0.0, 0.1, 0.2, 0.3 on a function of the form $(1 - x^2)^n$, n = 0.1 to 0.5. The graphs are shown in Fig. 5. It is seen from this that the original distribution undergoes strong changes as σ increases. This means that when the width of the stellar profile is significant, the observed distribution is more characteristic of the state of the Earth's atmosphere than of the true intensity distribution across the diameter of the planet.

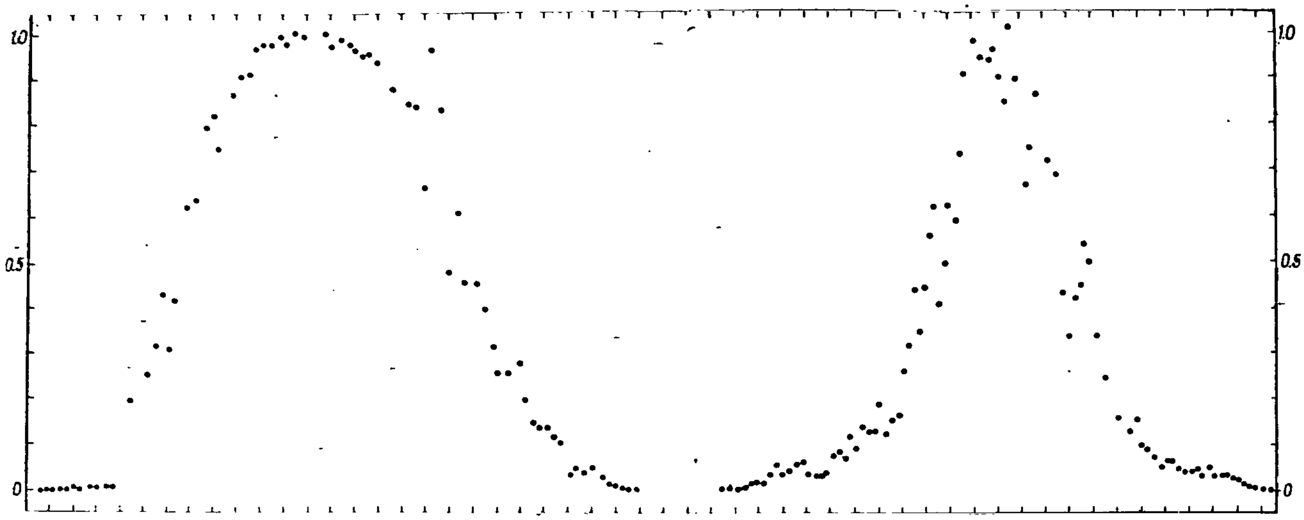


Figure 2.a

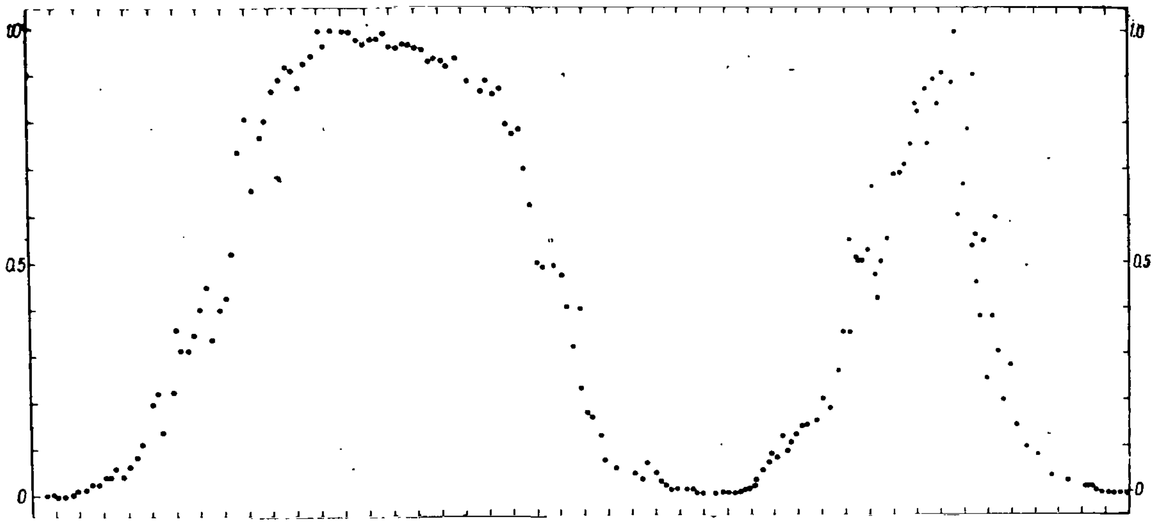


Figure 2.b

Figure 2. Distribution of Brightness Over the Disk of Mars and Stellar Profiles for 13/14 March 1965. (W♂ to the right.) Relative Intensity is Plotted Along the Ordinate Axis. On the Abscissa Axis Each Division Equals 1".

Wavelength, nm: a) 600, b) 530, c) 510, d) 475, e) 450, f) 430, g) 420, h) 390, i) 355.

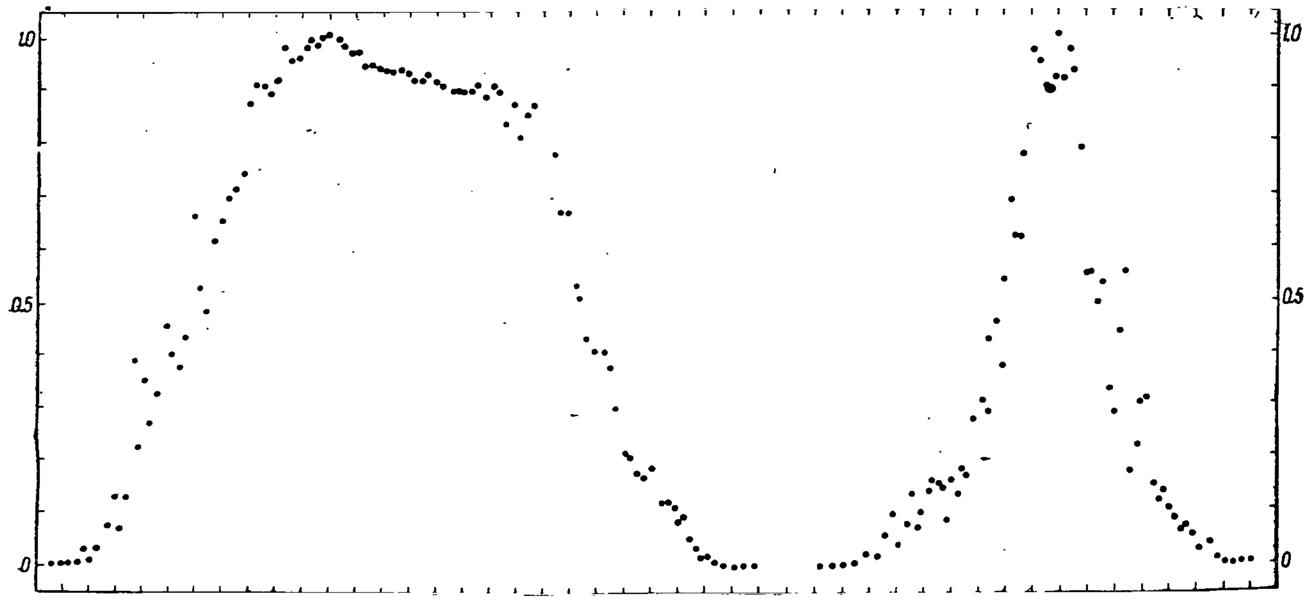


Figure 2.c

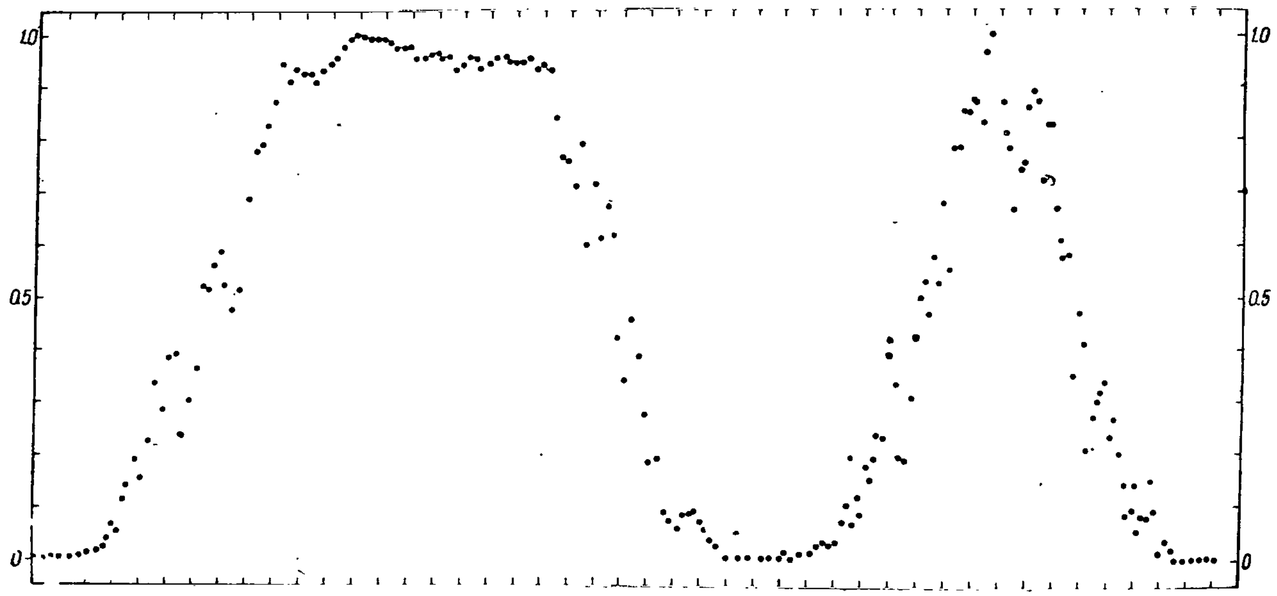


Figure 2.d

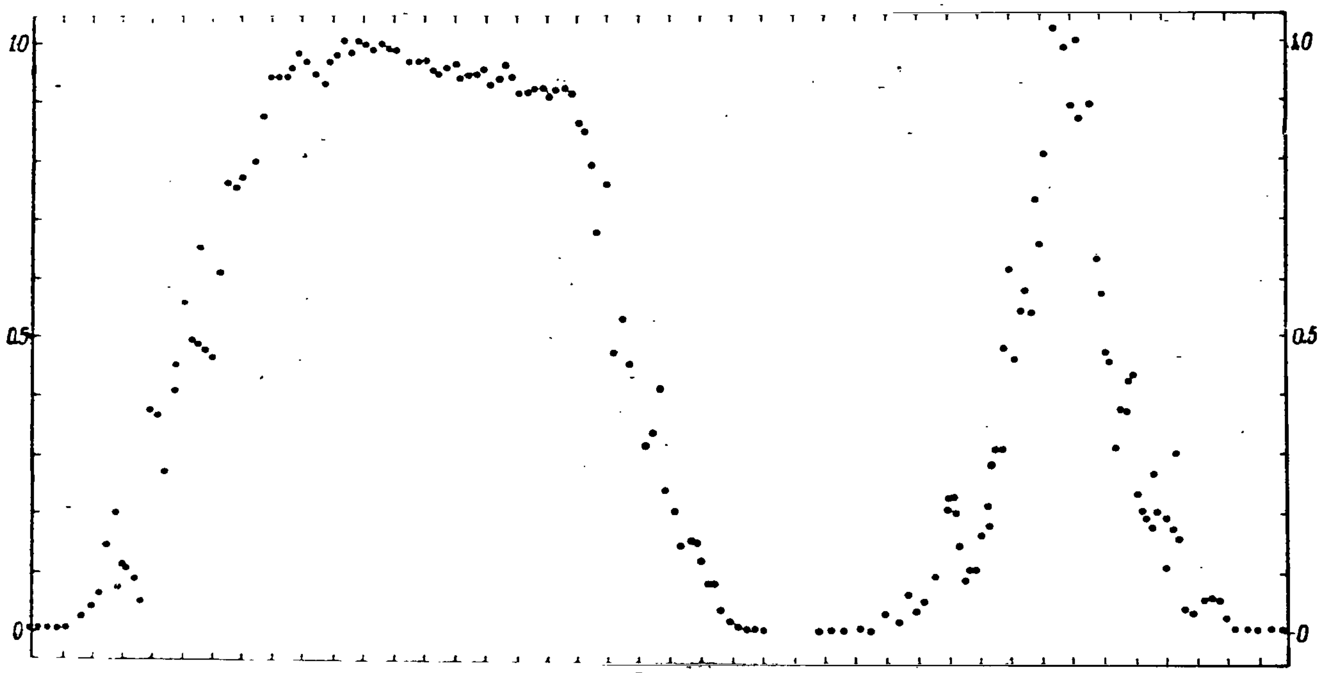


Figure 2.e

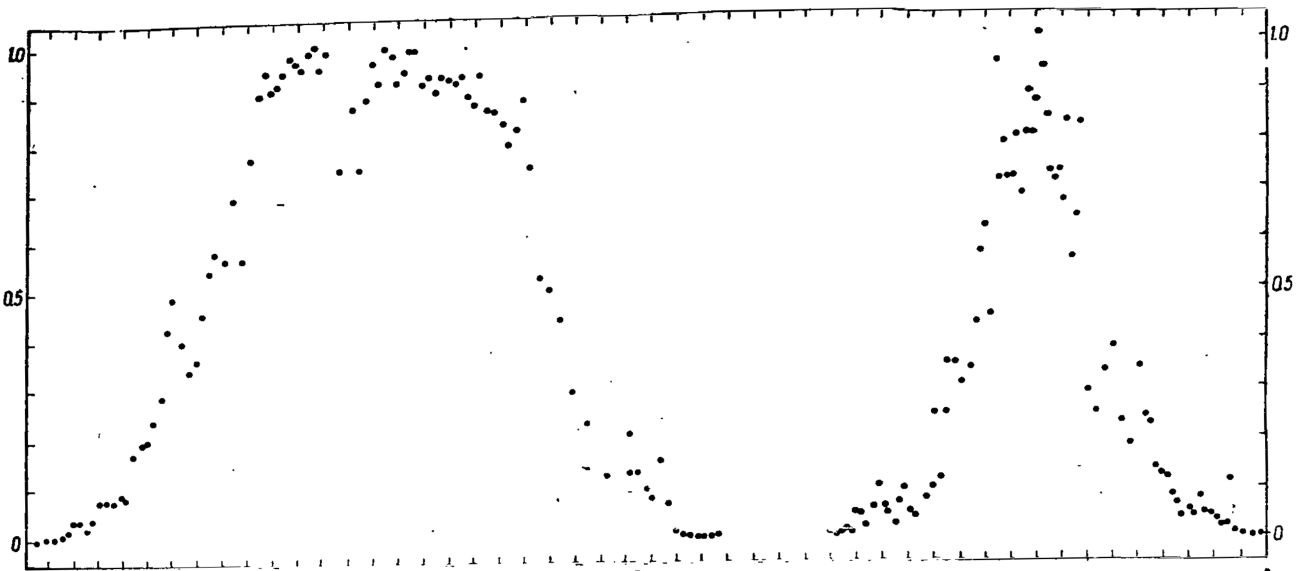


Figure 2.f

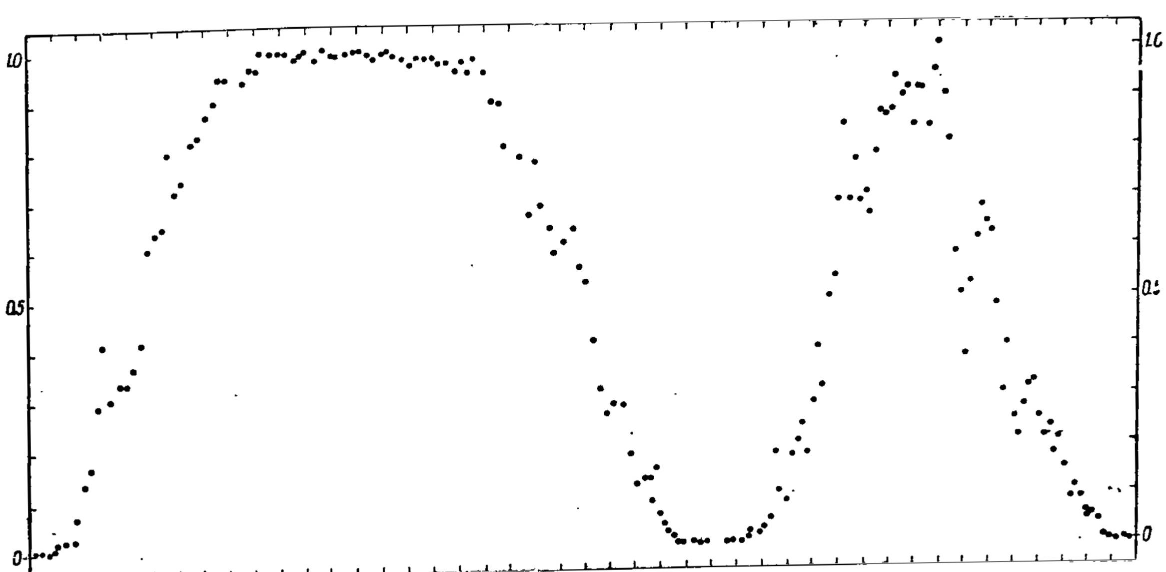


Figure 2.g

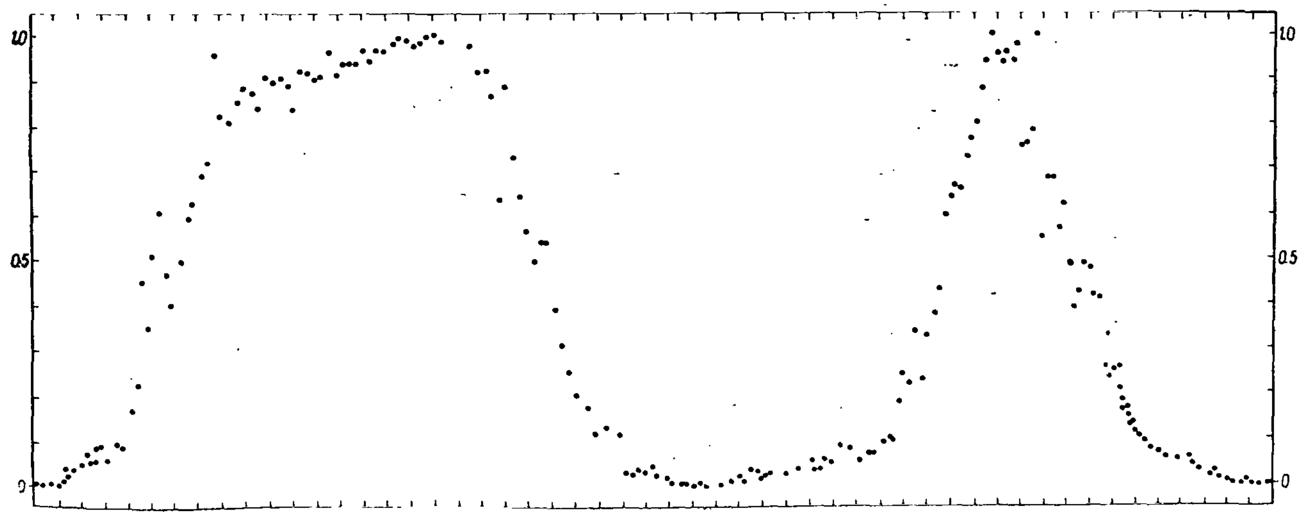


Figure 2.h

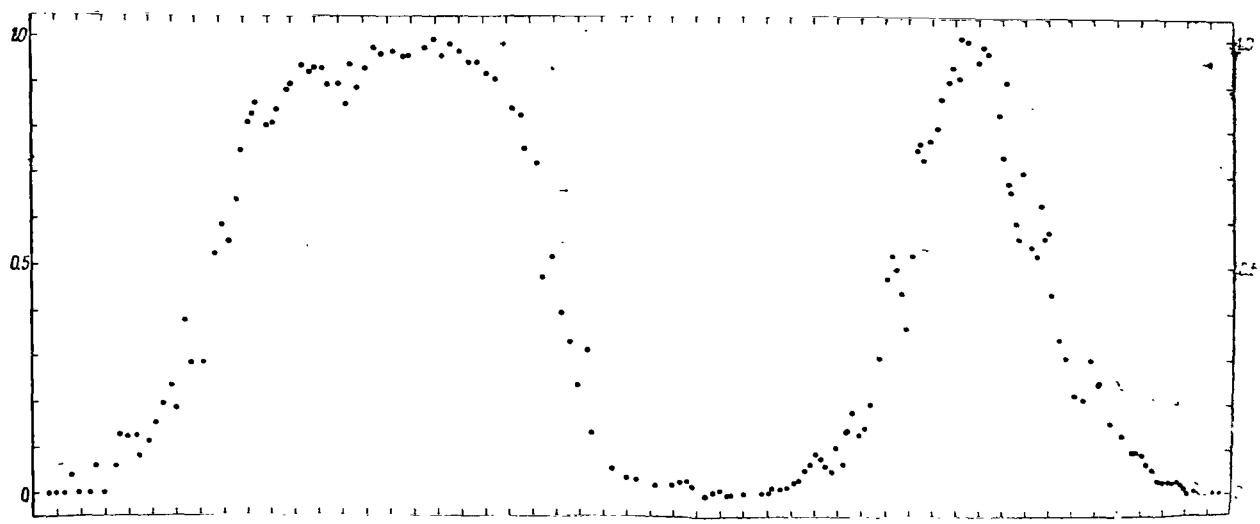


Figure 2.i

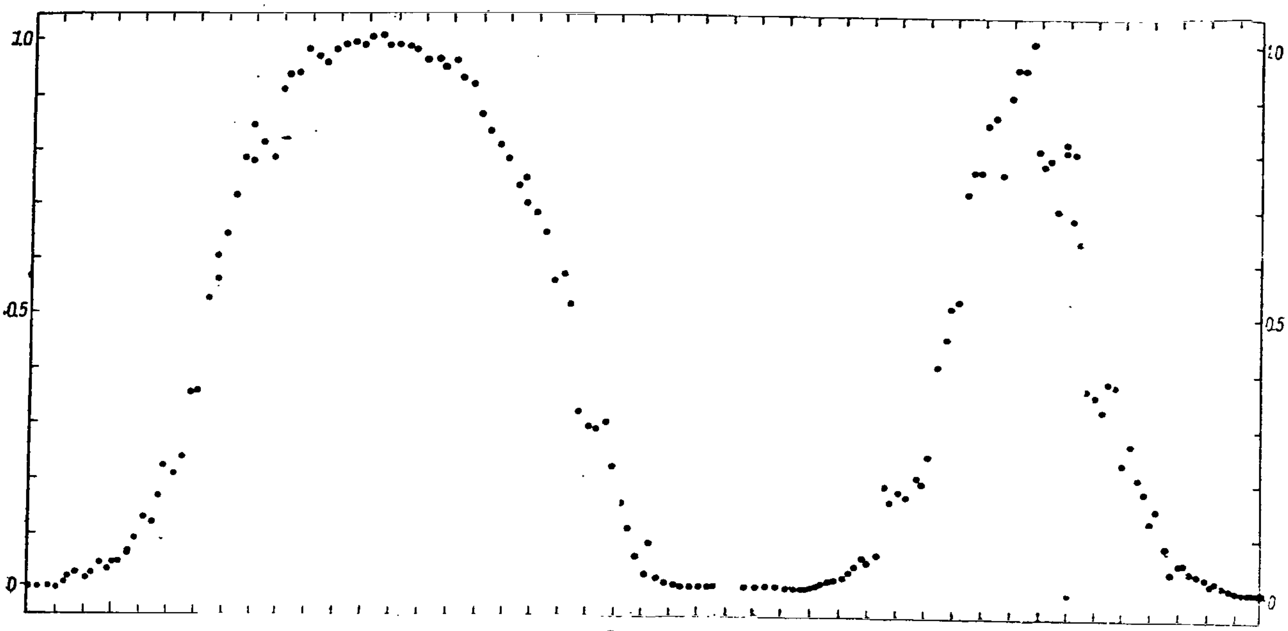


Figure 3a

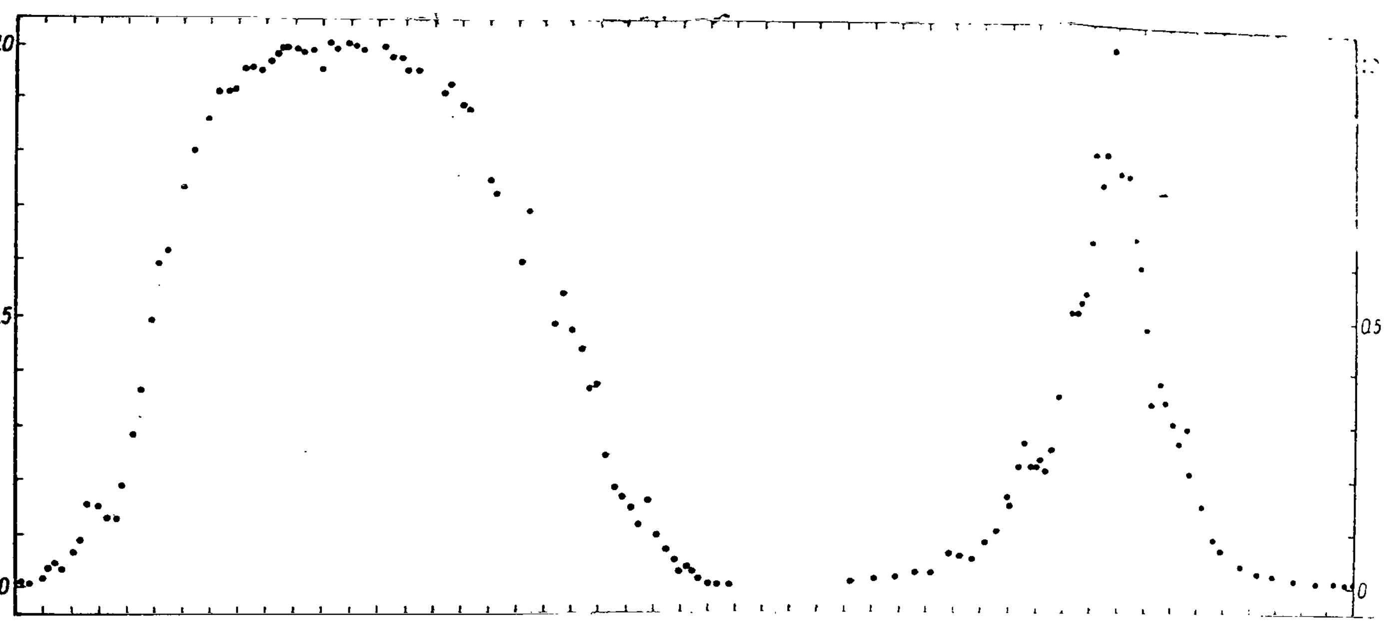


Figure 3b

Figure 3. Distribution of Brightness Across the Disk of Mars and Stellar Profiles for 23/24 March 1965.

Wavelength, nm: a) 600, b) 560, c) 530, d) 450, e) 430, f) 390, g) 355.

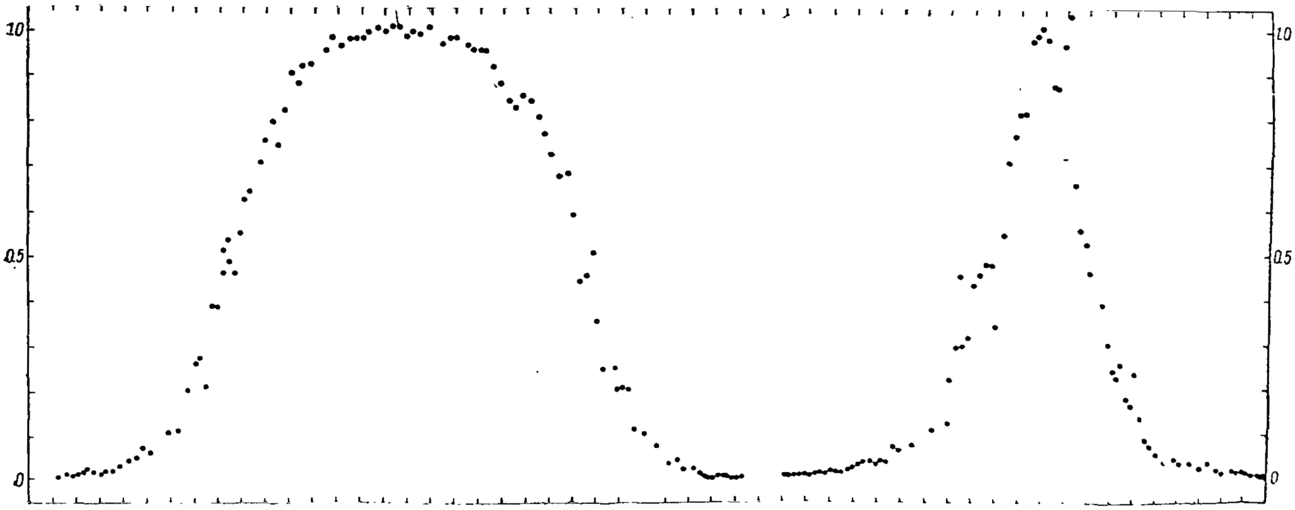


Figure 3.c

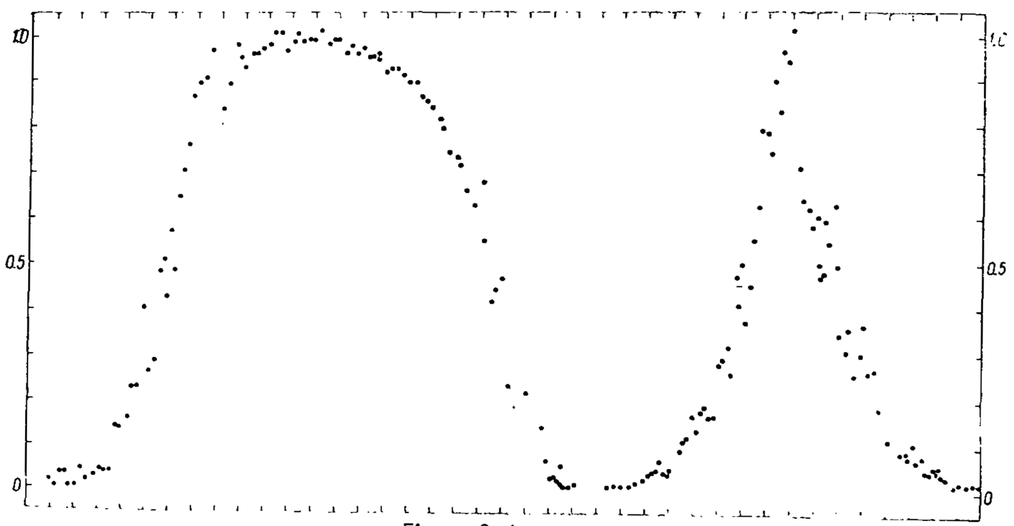
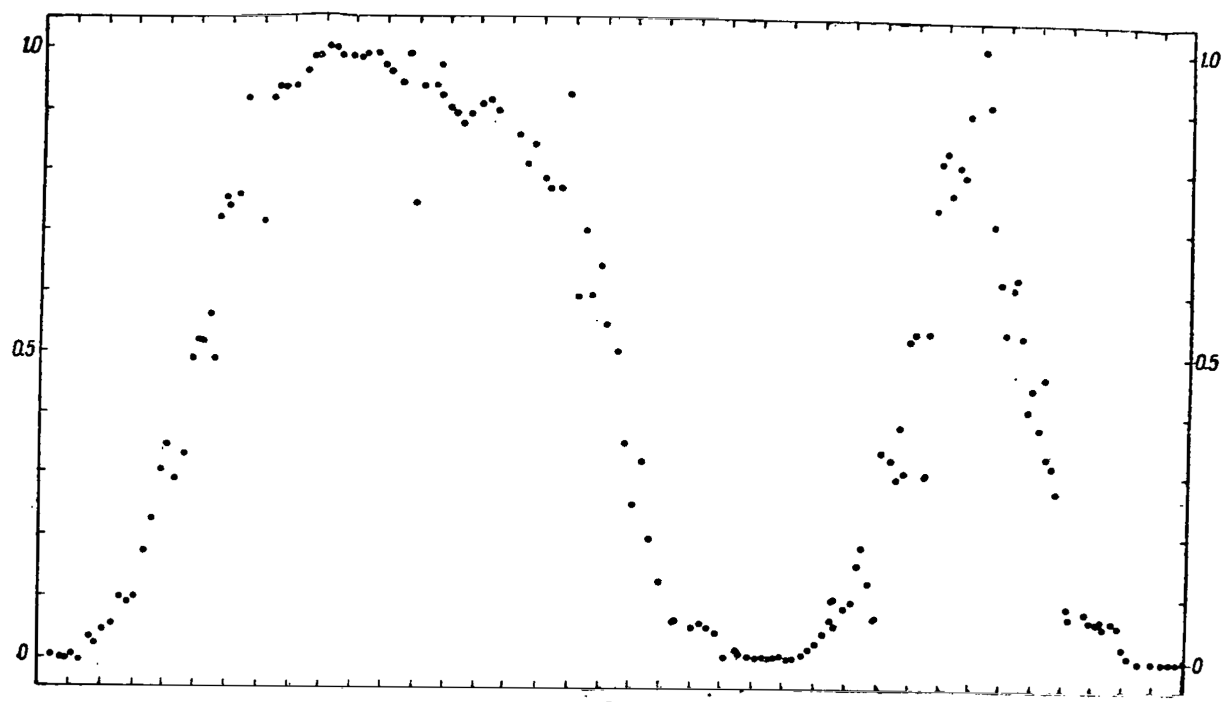


Figure 3.d



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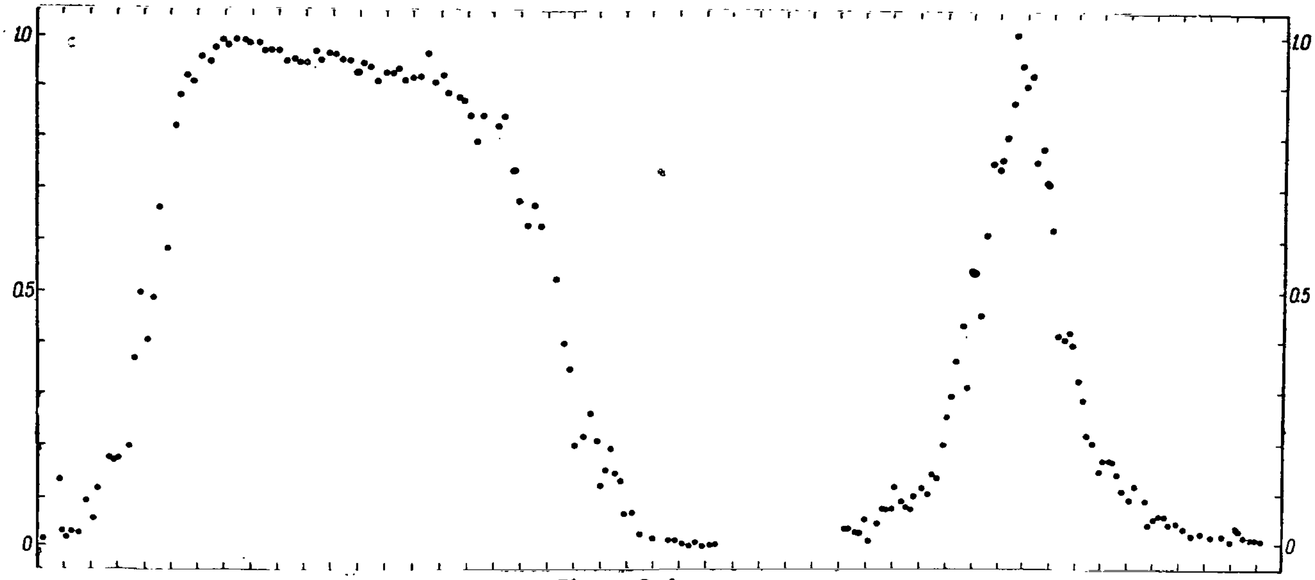

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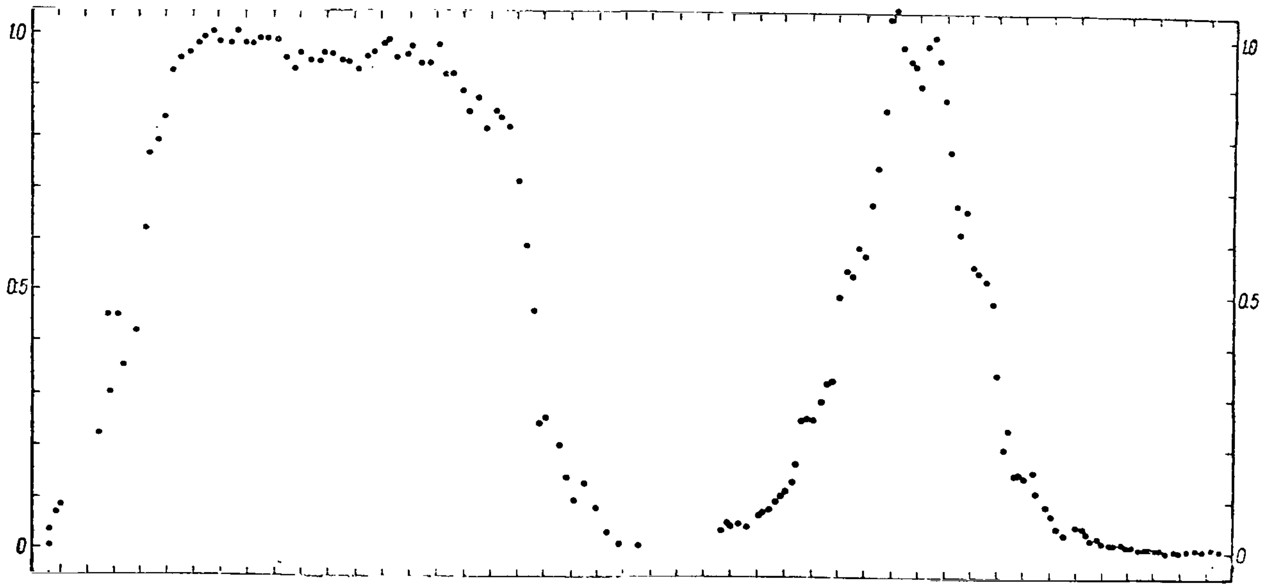


Figure 3.g

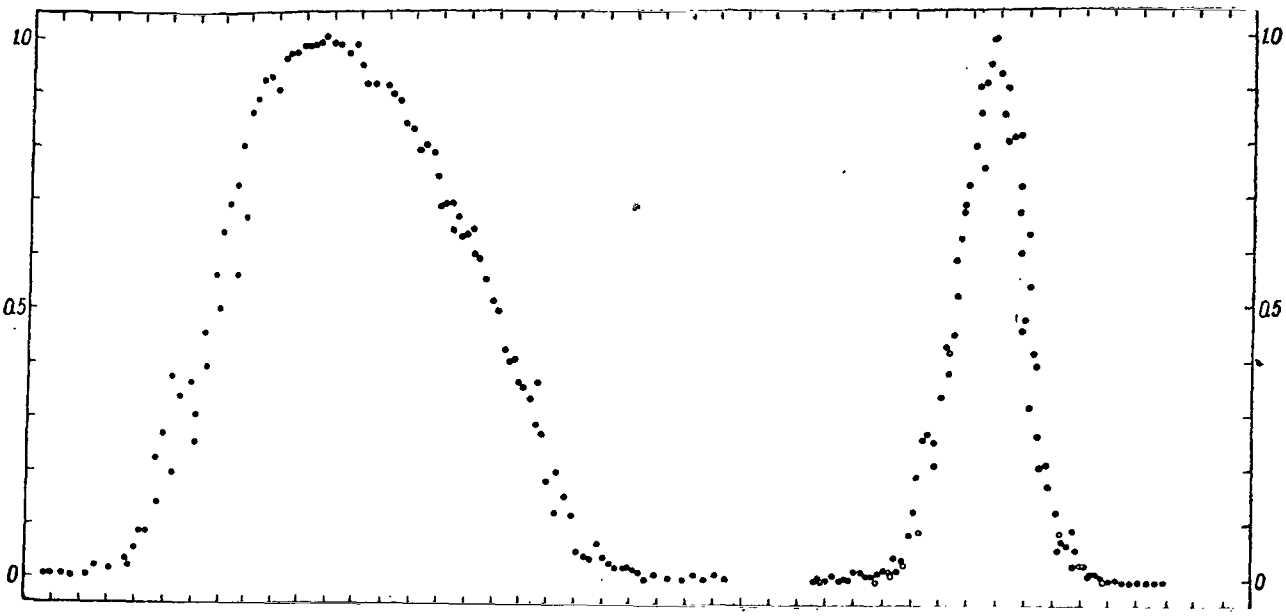


Figure 4. a

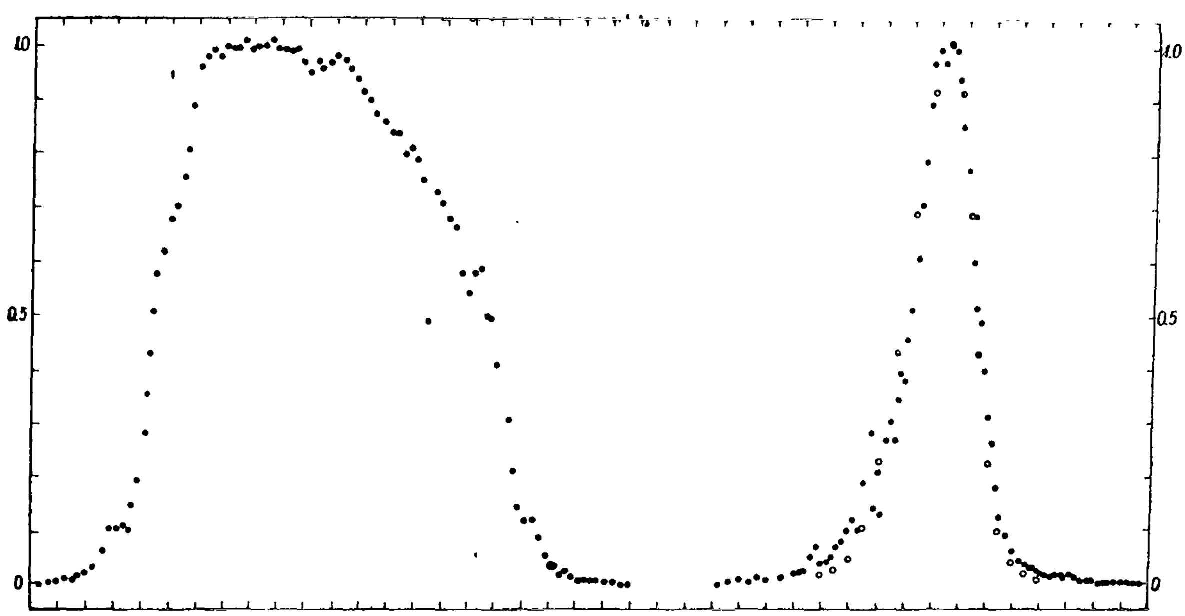


Figure 4.b

Figure 4. Distribution of Brightness Across the Disk of Mars and Stellar Profiles for 6/7 April 1965.

Wavelength, nm: a) 600, b) 430, c) 475, d) 430, e) 390, f) 355.

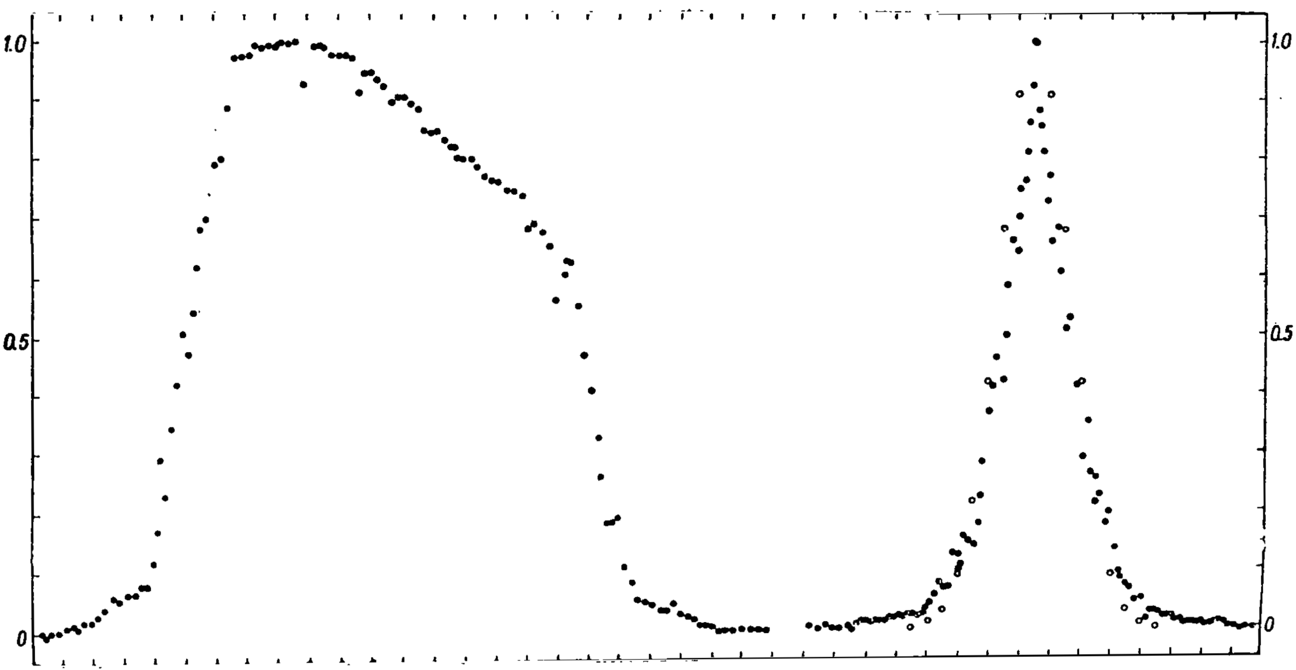


Figure 4.c

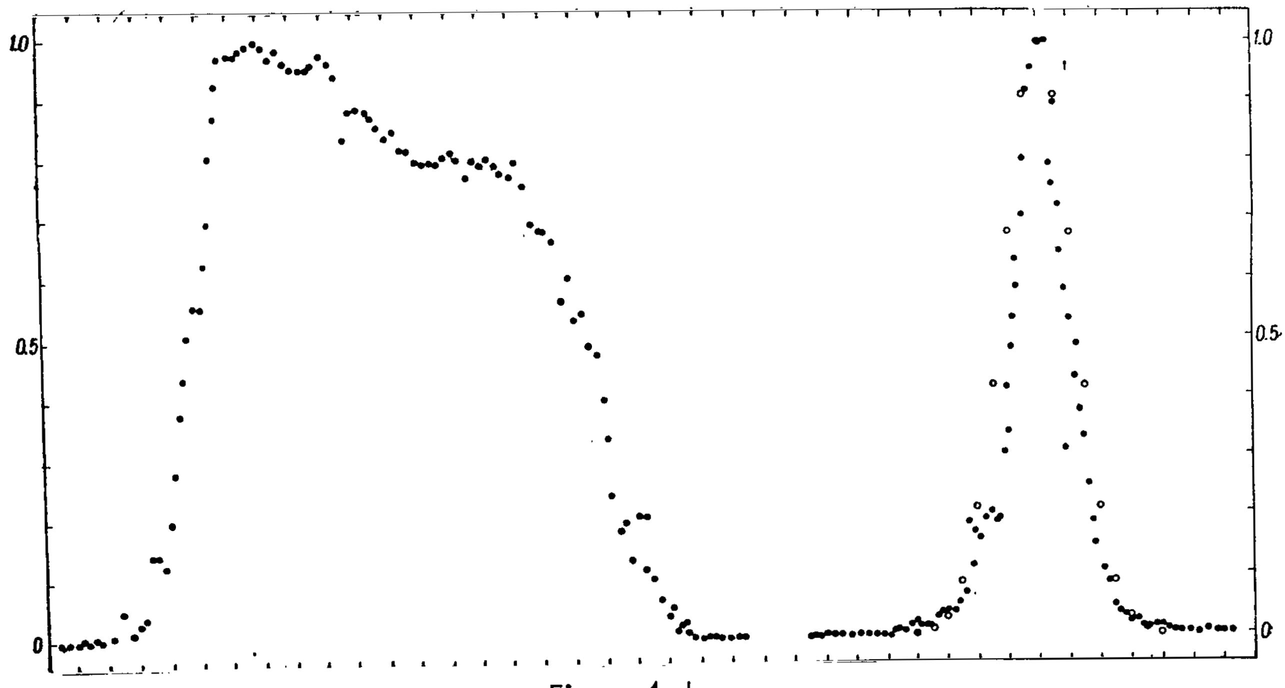
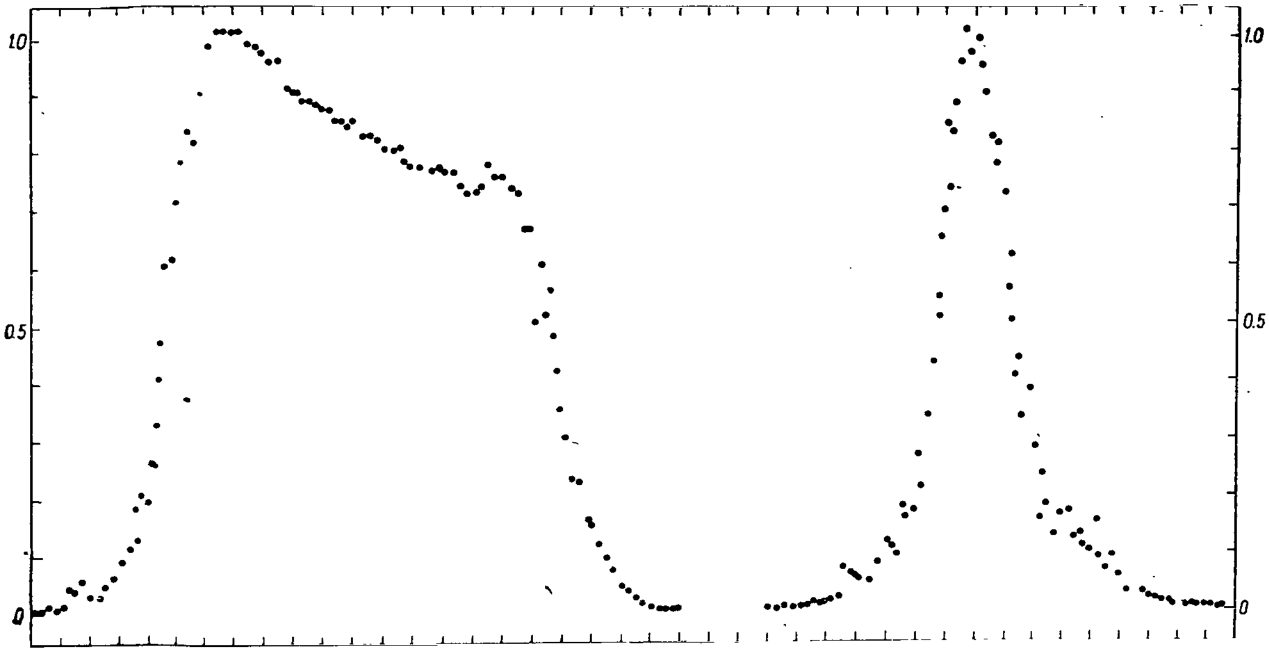


Figure 4.d



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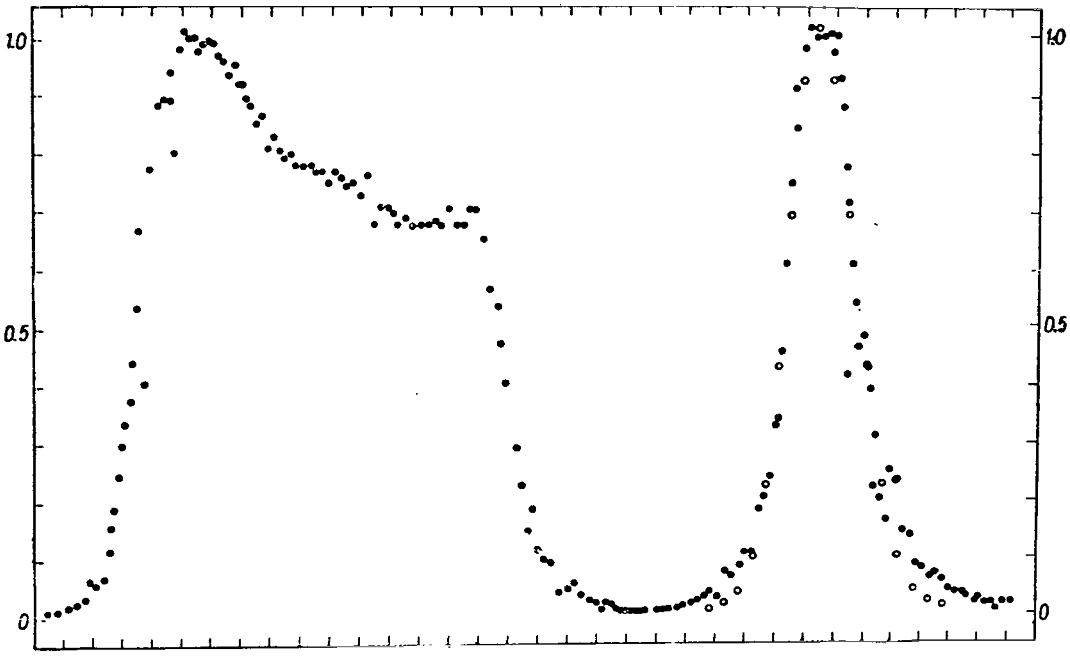

Figure 4.f

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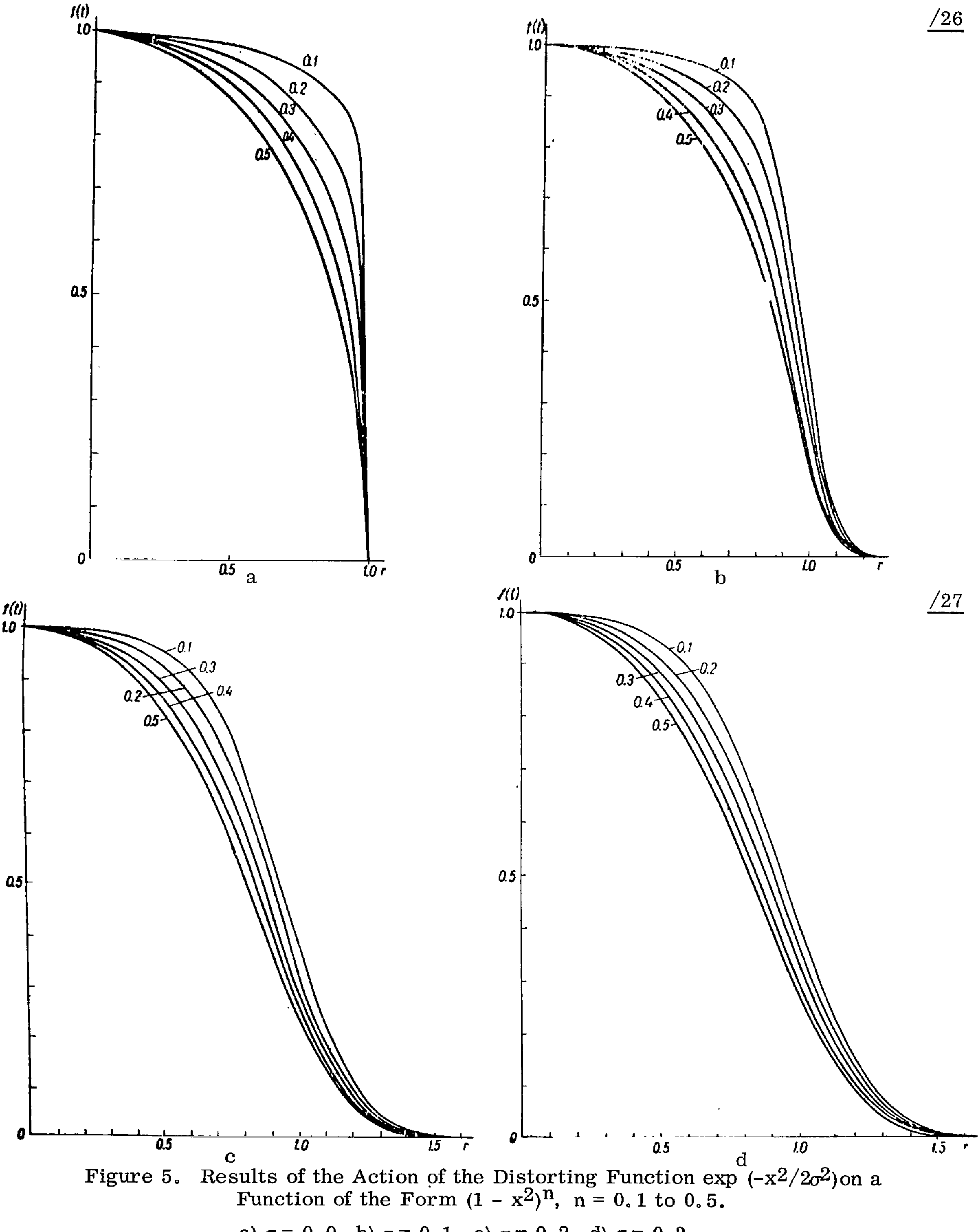

Figure 5. Results of the Action of the Distorting Function exp $(-x^2/2\sigma^2)$ on a Function of the Form $(1 - x^2)^n$, n = 0.1 to 0.5.

a) $\sigma = 0.0$, b) $\sigma = 0.1$, c) $\sigma = 0.2$, d) $\sigma = 0.3$.

As far as the parameter n is concerned, which characterizes the behavior of brightness along the diameter, it is always obtained higher than the true value. Preliminary corrections of observed curves along a radius of Mars for /28
600 nm are given in [20].

The solution of the problem will be more correct if it is assumed that the distribution of brightness over the disk of the planet is spherically symmetric even in a zone of width of the order of σ which encompasses the section. Then to solve the problem in this case it is sufficient to have one diametric photometric section.

The latter assumption holds for arbitrary values of the phase angle, if the direction of the section is close to the intensity equator. The most favorable moment is that of an opposition.

As a whole, the problem of regenerating the true distribution is extremely complex mathematically, since it involves a special algorithm for the solution of the corresponding integral equation, which is due to the piecewise continuous character of the function sought. We are presently working on this.

As regards the distorting function $K(\vec{z}) = K(\vec{r} - \vec{t})$, it is determined from

$$G(\eta) = A \int_{-\infty}^{\infty} K(\vec{z})\, d\xi. \qquad (3)$$

Here $G(\eta)$ is the stellar profile obtained by observation with a slit, $|\vec{z}| = \sqrt{\eta^2 + \xi^2}$. In the case when

$$K(\vec{z}) \sim \exp\left(-\frac{z^2}{2\sigma^2}\right),$$

then also

$$G(\eta) \sim \exp\left(-\frac{z^2}{2\sigma^2}\right).$$

In any case, when $K(\vec{z})$ has spherical symmetry, Eq. (3) has an exact solution.

In conclusion, we give a brief description of the obtained photometric sections of Mars.

As has already been mentioned, the diaphragm of the electrometer was removed mainly along the continental regions of the northern hemisphereof Mars. /29
Hence, only rarely are details with weak contrast visible in the sections. This pertains to filters with $\lambda_{eff} \geq 510$ nm. With the other filters, the visually conspicous Wright clouds located on the eastern and western edges of the disk are well traced out. The combined effect of the homogeneous atmosphere and the Wright clouds leads to a distinct decrease in the steepness of the curves in the limits of the ephemeridal diameter in the shortwave spectral region.

As a rule, the width of the stellar profiles for a given date varies little with wavelength; hence, the obtained behavior of the steepness of the curves over the spectrum is close to the actual one.

From the sections obtained at opposition (13/14 March), we found the ratio of the brightness at the edge (r/R = 0.9) to that in the center of the disk for each filter. These data are given in the table:

λ, nm	355	390	430	450	475	510	530	600
I_r/I_0	0.68	·0.70	0.65	0.70	0.72	0.62	0.60	0.44

As expected, the ratio for λ_{eff} = 600 nm corresponds to the value of the cosine of the angle of incidence (64°). Since for this date the stellar profiles were very wide, one can expect that after correction the behavior of the curve will change significantly toward a decrease of the limb darkening.

It is interesting that from our observations in 1963 [17], the brightness distribution for λ_{eff} = 355 nm was almost the same as for λ_{eff} = 600 nm, which was explained by the presence of an intrinsic absorption in the Martian atmosphere. The absence of this effect in 1965 is evidently due to the rather intense Wright regions.

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