CORNELL UNIVERSITY

Center for Radiophysics and Space Research

ITHACA, N. Y.

NASA CR 108491

CENTER FOR RADIOPHYSICS AND SPACE RESEARCH
CORNELL UNIVERSITY
ITHACA, NEW YORK

June 1970

NAS 9-8018

CRSR 386

THE 1969 OPPOSITION EFFECT OF MARS: FULL DISC, SYRTIS MAJOR AND ARABIA

Brian O'Leary and Lawrence Jackel

ABSTRACT

Photometry of the full disc of Mars near opposition 1969 confirm the existence of a moderate opposition effect, i.e. a non-linear surge in brightness toward zero phase. Observations of small areas on the disc suggest a very strong opposition effect for Syrtis Major; the extent is somewhat similar to the lunar case.

We also confirm a 13% absorption feature near 1.0μ in the ratio spectrum Syrtis Major/Arabia. Contrary to earlier analyses, the color of Syrtis Major/Arabia appears to have changed from previous observations such that the brightness contrast is greater in the red and near-infrared than at shorter wavelengths.

More observations are needed to verify the pronounced opposition effect of Syrtis Major and its possible color change. Further optical studies of oxidized basalts in the laboratory will be helpful in determining whether differential properties of Martian dark and bright areas may be due to particle size modulation, extent of oxidation, microstructure, composition, or some combination of these factors.

INTRODUCTION

During the 1969 apparition of Mars, one of us (O'Leary) made photometric measurements of the planet near the opposition itself from Cerro Tololo Observatory in La Serena, Chile. The objectives of the observations were to: confirm the existence and properties of a non-linear surge in brightness of the planet toward zero phase at very small phase angles (the "opposition effect"), determine the zero phase magnitude of Mars in the 1969 opposition, investigate the planet's rotational light curve, attempt to differentiate between the opposition effects of dark areas and bright areas, and study the spectral dependence of the reflectivities of Syrtis Major and Arabia between 0.80 and 1.15μ. We describe the motivation behind these objectives in the following paragraphs.

The opposition effect property is common to all diffusely reflecting materials, and its extent varies widely from sample to sample. For example, it is well-known that the Moon exhibits a very strong opposition effect for phase angles $\alpha < 5^{\circ}$ (Barabashev, 1922; Wildey and Pohn, 1964; Gehrels, Coffeen and Owings, 1964; van Diggelen, 1965). The most widely accepted interpretation of the pronounced lunar opposition effect is an intricate three-dimensional ("fairy castle") structure of the fine-grained lunar material (Hapke, 1963). Such a structure would be at least partly due to micrometeoroid bombardment and/or exposure of the lunar surface to the solar wind.

It is therefore interesting to apply this analysis to the case of Mars: is its opposition effect as pronounced as the Moon's or is it more typical of some terrestrial substances? Which materials may be ruled out as predominant coverings for the Martian surface because of large discrepancies in the opposition effect? A clear definition of the Martian opposition effect would add a significant piece of information in attempts to identify surface composition and structure.

One problem with measuring this property of Mars is that the planet rarely passes through sufficiently small phase angles because of the inclination of its orbit to the ecliptic plane. In the thirty years preceding the 1967 apparition, phase angles less than 2° were achieved at only three oppositions. Fortunately, both the 1967 and 1969 oppositions provided very small minimum phase angles — $1\overset{\circ}{.}2$ and $1\overset{\circ}{.}3$ respectively.

In 1967 a moderate opposition effect was observed (O'Leary, 1967a; Bugaenko, Koval', and Morozhenko, 1967); its existence is also suggested from previous observations (de Vaucouleurs, 1968). The extent of the Martian opposition effect was found to be much less than those for the Moon and for several ferric oxides investigated in the laboratory (O'Leary, 1967b; O'Leary and Rea, 1968). These data, when combined with other comparisons between the optical properties of Mars and laboratory samples, led Rea and O'Leary to conclude that the predominant covering for the Martian surface is not limonite, goethite or hematite.

Another interesting aspect of the Martian opposition effect is the role of aerosols in its atmosphere. The anomolously large effect observed in the blue and ultraviolet, if caused by an atmospheric effect, cannot be explained simply by Raleigh scattering by molecules; one must resort to aerosols (O'Leary 1967a and b; O'Leary and Rea, 1968, Mead, 1970).

The major purpose of the 1969 observations described herein is to confirm and to characterize further the Martian opposition effect. Byproducts of the observations are differentiation between the opposition effects of the dark and bright areas, the determination of the absolute photometric parameters of Mars near opposition, and a study of the ratio of brightnesses of Syrtis Major to Arabia near one micron as compared with earlier observations (McCord, 1969; McCord and Adams, 1969). None of these additional objectives had been accomplished during the 1967 observations because poor observing conditions prevented isolating small areas for photometric measurements.

THE OBSERVATIONS

The observations were made at the Cerro Tololo 36-inch telescope during the 1969 opposition in late May and early June. The available clear nights of observation corresponded to Martian phase angles ranging between $1^{\circ}.3$ and $3^{\circ}.5$. An RCA 7102 photomultiplier tube-coldbox assembly was used in conjunction with a series of interference filters whose wavelengths and bandwidths are listed in Table I. The seeing was occasionally outstanding ($\lesssim$ 1 second of arc), which permitted study of small areas such as Syrtis Major and Arabia with a 1 arc-second diaphragm. These small area studies were performed in two ways: (1) scans across the Martian disc and (2) isolation of Syrtis Major and Arabia. There is obviously great difficulty in obtaining accurate photometric information of a small area on a planet. Although Syrtis Major was 2 to 3 seconds of arc in size, the brightness varies within the region, with the resolution due to seeing changing from moment to moment. Nevertheless, in times of excellent seeing, it was possible to isolate the darkest region within Syrtis Major (chosen in such a way as to minimize the deflection observed on the strip chart recorder), and to dwell on such an area for a minute or two without an appreciable change in brightness. In this way, it was occasionally possible to run through seven filters at wavelengths between 0.80 and 1.15μ and repeat the same measurements with a high degree of accuracy.

The major program was full disc photometry in 4 colors (Table I). These observations did not depend on seeing, and, providing the weather was clear, it was possible to observe the entire disc at preplanned times each evening corresponding to 15-degree intervals in Martian central meridians, or about 1 hour intervals in time. Such planning was necessary because of the well-known changes of Martian brightness with its rotation. The observations could then be compared from night to night to derive the opposition effect in a manner somewhat similar to that described earlier (O'Leary, 1967b).

Each observation consisted of taking three one-second integrations of the brightness of Mars-plus-sky and sky in each color, monitoring the brightness of a radium standard, repeating the process for a comparison star, repeating it again for Mars, and going to another comparison star. The use of the radium standard allowed us to correct for short-term fluctuations in the response of the photometric apparatus. The comparison stars used were α Sco and θ Sco. It was noticed that α Sco's brightness had varied since Johnson's observations of its standard magnitude (Johnson et al, 1966). Absolute magnitudes of α Sco for the period of the 1969 Mars observations were determined by comparing several measurements of α Sco with θ Sco and using Johnson's values of θ Sco as an absolute standard. We found no evidence that brightness of α Sco varied over the five-day period of the 1969 Mars observations.

We used mean extinction coefficients for Cerro Tololo; large errors in these values during any given night would introduce only minor errors in the derived magnitude of Mars because of the proximity of these stars to Mars in the sky. Second-order extinction was negligible because of the narrow bandpass of each filter.

The "absolute" magnitudes of Mars, i.e. magnitude reduced to unit distance from the Earth and Sun, M, were determined by standard photometric reduction procedures (Hardie, 1962; O'Leary, 1967b): after extinction corrections, the magnitudes and colors of Mars are compared to those of the comparison star and transformed to the standard UBVRI system by means of transformation coefficients determined by observing several standard stars near the zenith (The Arizona-Tonantzintla Catalogue, 1965; Johnson _et al_, 1966). Unlike the 1967 case, the 1969 observations produced only small transformation errors, and the actual values of the derived Martian magnitudes are expected to be accurate to ~ 0.01 mag. in B, V and R. The observations at 1.2μ were not transformed to a standard system, because magnitudes for the standard stars are not available. Therefore, the I" magnitude scale is arbitrary.

The observed apparent Martian magnitudes, m, were changed to "absolute" magnitudes, M, by the equation:

$$M = m - 5 \log rd - 2.5 \log f(\alpha)$$

where r is Mars' distance from the Sun, d is Mars' distance from the Earth, and $f(\alpha)$ is the fraction of the illuminated disk as a function of phase angle. At $\alpha = 0^{\circ}$, M becomes the "opposition magnitude", M(1,0), the magnitude of Mars at opposition reduced to unit distance from the sun and earth (Harris, 1961).

RESULTS: FULL DISK STUDIES

Values of the absolute magnitude of Mars versus central meridian, λ_c, are plotted in Figure 1 for each night of observation. As we mentioned earlier, the observations were purposely clustered at 15° intervals and each data point is an average for each cluster. As would be expected, the brightness of Mars varies with its rotation; the amplitude of the variation is roughly 0.15 mag. at 0.55μ. It is interesting to compare rotation curves from opposition to opposition to check the amplitude of the variation as a function of the aspect of the Martian polar axis as seen from Earth. Table II shows the tabulation of aerocentric declination of the Earth, D_E, versus rotation curve amplitude in V magnitude, $\Delta V = V(\lambda_c = 180^{\circ}) - V(\lambda_c = 270^{\circ})$. The 1969 results show a slightly greater rotational brightness variation than would be expected from earlier observations, but the agreement is still reasonable in view of expected longterm variations of features on the Martian disc.

This stronger-than-expected rotational dependence is most likely attributable to the presence of clouds in the Martian atmosphere. The reason for believing this to be the case is that observations in the blue (Fig. 1) show a rotational variation of $\sim$0.1 mag., considerably greater than has been previously reported (e.g., O'Leary, 1967b). Though a slight surface contrast between dark and bright areas was observed in the blue during the 1969 observations, this alone would not be sufficient to explain such a large variation in Martian brightness with rotation.

The next step in the reductions was the determination of the Martian opposition effect. Unfortunately, circumstances prevented observations to be made at phase angles greater than $3\overset{\circ}{.}5$, but there were still a sufficient number of data points to derive the opposition effect with reasonably high precision. Table III lists the phase angles covered each night. Each phase curve was derived by performing a linear interpolation, if necessary, between points on Fig. 1 for those values of Martian magnitude at $\lambda_c = 210^\circ$, 225°, 240°, 270° and 285° for each phase angle. Using the method of least squares a straight line was fit to magnitude vs. phase angle for each λ_c. It was then possible to obtain values of the magnitude at $\alpha = 0^\circ$ and the slope of the phase function. Although the slope is not strictly linear between

$\alpha = 3\overset{\circ}{.}5$ and $1\overset{\circ}{.}3$ because of the opposition effect itself, the best fit is close enough to a straight line for the purposes of this discussion. The extrapolated zero phase magnitudes, M(1,0), for each central meridian appear in figure 1.

Table IV tabulates the values of the phase function slopes between $\alpha = 1\overset{\circ}{.}2$ and $3\overset{\circ}{.}5$ and their probable errors. It is immediately apparent that there is a tendency for the opposition effect to be greater for those observations which include several dark areas ($\lambda_c = 270^\circ$ and 285°) than those which emphasize bright areas ($\lambda_c = 210^\circ$). We therefore suggest that the Martian dark areas have a greater opposition effect than the bright areas; this behavior can be expected from previous analyses which show an inverse relation between the albedo of a substance and its opposition effect (O'Leary and Rea, 1968).

Table V shows the mean slopes of the phase function for each color between $\alpha = 1\overset{\circ}{.}3$ and $3\overset{\circ}{.}5$. We derived these mean slopes by weighting slopes for each λ_c by the square of the inverse of the error of the individual slopes. The derived slope values in Table V are not critically dependent on the weighting technique; the maximum uncertainty in these values is about 10%. There is no question of the existence of a Martian opposition effect; in fact, it is more pronounced by about 30% than that observed in 1967, and 3 to 4 times steeper (depending on color) than the well-known linear phase curve for $\alpha \gtrsim 15^{\circ}$. The apparent discrepancy between the 1967 and 1969 observations can probably be explained by uncertainties in the phase curve slope for $\alpha \lesssim 3^{\circ}$ in the 1967 observations, and the fact that the 1969 observations encompassed more dark areas than the 1967 observations.

Tables IV and V also list values of M(1,0) obtained for the 1969 opposition. The mean values in Table V were found to be intermediate between the values derived from the 1967 opposition effect measurements, and those values deduced from previous observations (Harris, 1961; de Vaucouleurs, 1964) without considering the opposition effect. This seemed somewhat surprising in view of the apparently more pronounced opposition effect in 1969 then in 1967; one would expect M(1,0) for Mars to be brighter, not fainter, in 1969. There are probably several reasons for the discrepancy of some 0.13 to 0.16 magnitude: (1) the 1967 observations were centered at $\lambda_c = 180^{\circ}$ whereas the 1969 observations were centered at $\lambda_c = 240^{\circ}$, where Mars is several hundredths of a magnitude darker, (2) a curvilinear rather than linear extrapolation of the 1969 data would yield brighter magnitudes, (3) the fitting of the 1967 curves to the linear phase curve for $\alpha \gtrsim 15^{\circ}$ could have been in error by as much as .03 mag. (O'Leary 1967a and b), and (4) Mars may have been intrinsically fainter in 1969 than in most previous oppositions because of seasonal and meteorological variations (for example, the size of the polar cap in the 1969 opposition was very small). Harris (1961) has reported brightness variations of up to 0.18 mag. between oppositions.

The perplexing question arises, at which intervals of Martian rotation, at what position of its polar axis with respect to the observer, and during which Martian season does one define M(1,0)? This question is important from the point of view of deriving the geometric albedo and other photometric parameters of Mars, and has not been raised in any detail in the previous literature. Perhaps a procedure could be adopted whereby standard rotational-light curves of Mars can be related to a given observation; the standard curve would yield a mean value of magnitude integrated over that rotation. The complications are numerous, however: as Table II shows, the amplitude of the standard curve between two selected λ_c can vary from 0.08 to 0.15, depending on the aspect of the Martian polar axis with respect to the observer, and the Martian brightness may intrinsically change because of seasonal and meterological phenomena (e.g., polar cap size).

Our conclusion is that any zero phase magnitude of Mars determined during a given apparition could conceivably disagree with previous observations by as much as 0.2 mag. A large error bar must be put on the predicted geometric albedo of the planet for any future observations, say, from a spacecraft experiment, although the photometric parameters revised by O'Leary (1967a, 1967b) are probably correct to within a few hundredths of a magnitude for the mean case which is determined from measurements made during many previous apparitions.

RESULTS: SMALL AREA STUDIES

Several scans were made across the Martian disc with a one arc-second diaphragm. Figure 2 shows a typical set of scans, smoothed over to eliminate amplifier noise, made at wavelengths ranging from 0.35 to 1.2μ. The scans were made in right ascension roughly along the Martian equator and were set in such a way to pass through the darkest area within Syrtis Major (scans were repeated to make certain the darkest area was within each scan). The large maxima in the scans represents the bright area Arabia, whose reflectivity values in Fig. 2 were estimated in terms of the expected normal albedo from previous data (O'Leary, 1967a and b; O'Leary and Rea, 1968; McCord, 1969; McCord and Adams, 1969).

The reduction in contrast between bright and dark areas toward shorter wavelengths is well-known, but it is interesting to compare the ratios of intensities of Arabia to Syrtis Major, R_λ, with those obtained from earlier observations (Younkin, 1966; McCord, 1969; McCord and Adams, 1969). During the 1967 apparition McCord and Adams found that, for a given Martian phase angle and date, a single "fitting factor", f, could be multiplied by their values of R_λ between 0.4 and 0.8μ to coincide exactly with those values determined earlier by Younkin (1966). In other words, there was no indication of color change with Martian season; only albedo changes were observed. During the passage of the Martian darkening wave through Syrtis Major in 1967, the value of f was 0.88 and one month later it became 1.06. There was no apparent relation between R_λ and phase angle in McCord's observations, but the interpretation of the observations is clouded by seasonal changes in Syrtis Major. Moreover, the region of the opposition effect was not encompassed.

It is interesting to compare our 1969 values of R_λ with earlier observations. Values of R_λ at 0.45 and 0.55μ derived from Figure 2 indicate a close match to Younkin's curve (Younkin, 1966), with f = 1.03. These observations were made on June 3, with Mars at a phase angle of 2°.77. However, observations between wavelengths 0.80 and 1.15μ, to be discussed later, show the fitting factor for that night to be f = 1.08. In other words, the contrast between Syrtis Major and Arabia was greater in the near-infrared than expected from previous observations, and there seemed to be a <u>color</u> change in one or the other area between earlier Martian apparitions and the 1969 one.

We next look at the dependence of R_λ on the opposition effect. Figure 3 shows three near-infrared scans across Syrtis Major and Arabia at phase angles 1°.35 (May 31), 1°.50

(June 1) and 2°77 (June 3), normalized to a reflectivity of 49% for Arabia. Inspection of Figure 3 suggests that the contrast between Syrtis Major and Arabia increased away from opposition, i.e. the opposition effect of Syrtis Major was greater than that for Arabia. This is in agreement with our analysis of full disc photometry showing the opposition effect of the Martian dark areas to be greater than that for the bright areas.

The difference in $dM/d\alpha$ implied by Figure 3 is $\Delta(dM/d\alpha) \sim$ 0.1 mag./deg., a sizable increment in the slope of the opposition effect from the mean full disc value of $dM/d\alpha \sim 0.03$ mag./deg. at 1.2μ. Such a large slope for Syrtis Major would make its opposition effect comparable to the Moon's.

How do these results compare quantitatively with the full disk studies? Inspection of Table IV indicates that such a large difference in opposition effects of dark and bright areas may be real: the slope of the full disc phase curve steepens some 0.01 to 0.02 mag./deg. when Syrtis Major and other dark areas come into full view ($\lambda_c = 270^\circ$ and 285°) with respect to prior positions of rotation at $\lambda_c = 210^\circ$ and 225°. The implication here is that a value of $\Delta(dM/d\alpha) \sim 0.1$ mag./deg. for the Arabia-Syrtis Major pair must be degraded by a factor of 5 to 10 to mimic the full-disc phase curve slope differences between $\lambda_c = 210^\circ$ to 285°. This range in degradation factors from area pairs to full disc encompasses those values estimated from both previous observations (O'Leary and Rea, 1968; McCord and Adams, 1969) and the present observations. It is therefore encouraging that two independent measures of opposition effect differences between dark and bright areas are in quantitative accord.

In their 1967 full disc studies O'Leary (1967b) and O'Leary and Rea (1968) did not detect any appreciable difference between the opposition effects of bright and dark areas. But at 0.83μ, there was a suggestion that the phase curve slope between $\alpha = 3^{o}$ and 7^{o} was .005 mag./deg. greater for $\lambda_c \sim 210^{o}$ (which includes some dark areas) than for $\lambda_c \sim 150^{o}$ (predominantly bright areas). The fact that the 1967 observations were less precise, made outside the major portion of the opposition effect, and the fact that Syrtis Major had not been included tend to argue against relying on them for such a subtle difference.

We performed further studies of Syrtis Major and Arabia with the one-second arc diaphragm through a series of filters running from 0.80 and 1.15μ. Figure 4 shows the resulting plot of the ratio $1/R_{\lambda}$, of Syrtis Major intensity to Arabia intensity, versus wavelength. We plot Younkin's points for comparison (Younkin, 1966). The general agreement in the shapes of the curves is good; the 1969 observations confirm a drop in reflectivity of Syrtis Major with respect to Arabia from 0.8 to 1.0μ of ~13%. McCord and Adams (1969) have suggested that the 1.0μ absorption band evident in the spectrum of Syrtis Major may be attributable to important differences in the composition of materials covering the dark and bright areas; the role of oxidized basalts may be a significant factor.

The most interesting aspect of Figure 4 is that, once again, the contrast between Syrtis Major and Arabia is greater somewhat away from opposition ($\alpha = 2\overset{\circ}{.}77$) than near opposition ($\alpha = 1\overset{\circ}{.}50$). We again suggest that the opposition effect of Syrtis Major is greater than that of Arabia. The fitting factor, f, to bring our results into accord with Younkin's is 1.00 for $\alpha = 1\overset{\circ}{.}50$ and 1.08 for $\alpha = 2\overset{\circ}{.}77$. Therefore, a third technique indicates that the opposition effect of Syrtis Major is $\Delta(dM/d\alpha) \sim 0.1$ mag./deg. greater than that of Arabia.

There is one final point to make concerning the apparent steepness of the opposition effect of Syrtis Major: this phenomenon only occurs for observations made in the red and near-infrared. Table IV shows the differences in the full disk phase curve slope, from $\lambda_c = 210^\circ$ and 225° to $\lambda_c = 270^\circ$ and 285°, to be $\Delta(dM/d\alpha) \sim 0.01$ to 0.02 mag./deg. at 1.2μ, ~0.006 mag./deg. at 0.70μ, and negligible in the blue and green. Even between 0.80μ and 1.15μ, the opposition effect of Syrtis Major seems to steepen toward longer wavelengths (Fig. 4). This may also explain the earlier observation that a steeper opposition effect curve occurred for dark areas than for bright areas at 0.83μ, but not at shorter wavelengths (O'Leary 1967b; O'Leary and Rea, 1968). However, this does not explain the fact that O'Leary and Rea did not detect any differences in opposition effects between bright and dark areas at 1.05μ, although the errors in such observations were about as great as the effect which was sought.

DISCUSSION

Accurate photometry of the integrated disc of Mars during the 1969 apparition confirmed the existence of a moderate opposition effect which had been reported for previous apparitions (O'Leary, 1967a, Bugaenko et al, 1967, de Vaucouleurs, 1968). As before, the effect was stronger in the blue than in the red and near-infrared, but in all cases, at about 2° phase angle, the slope of the phase curve steepened by a factor of 3 to 4 from the well-known linear phase curve of Mars for phase angles between $\sim 15^{\circ}$ and 45°.

The apparent lack of an opposition effect in 1965, reported by Irvine et al (1968), can probably be explained by the fact that their minimum phase angle was greater ($2^{\circ}.4$) and their error scatter was larger (~0.05 mag.). Nevertheless, their data do suggest the slight onset of an opposition effect between $\alpha = 5^{\circ}$ and $2^{\circ}.4$. In any case, the 1969 observations leave little doubt that a recurrent Martian opposition effect does exist. Opposition effects are appreciable for nearly all terrestrial samples, even including the standard diffuse reflector magnesium oxide (Oetking, 1966; O'Leary, 1967b; O'Leary and Rea, 1968), and any lack of a measurable opposition effect of a planetary surface would be very surprising.

Though the 1969 opposition effect was slightly stronger than the 1967 opposition effect, it is not nearly strong enough to be compatable with a predominant covering of the Martian surface by a ferric oxide powder such as limonite or goethite (O'Leary, 1967b; O'Leary and Rea, 1968).

On the other hand, the opposition effect of Syrtis Major appears to be very strong -- comparable in degree to the lunar opposition effect and greater than that of most terrestrial substances measured in the laboratory. This raises interesting questions about the structure and composition of the Martian dark areas: is there a complex, three-dimensional microstructure in the surface material as in the lunar case, and, if so, what physical process would cause this structure? Micrometeroid bombardment and the solar wind must be ruled out since neither can penetrate the Martian atmosphere. We discuss other possibilities in the following paragraphs.

It has been suggested that a modulation in particle size may explain the difference in albedo between bright and dark areas with the larger particles covering the dark areas. Rea (1964), Sagan and Pollack (1966), and Pollack and Sagan (1967) have discussed this possibility for limonite; Salisbury and Hunt (1968), for silicates slightly stained or coated with ferric oxides.

On the other hand, McCord and Adams (1969) reject the hypothesis of aeolian transport of finer-grained desert sand and dirt onto and from dark areas as the cause of seasonal changes in the dark areas, because they reported no color change between Syrtis Major and Arabia during the passage of the darkening wave in 1967; the aeolian hypothesis requires that there be seasonal color changes as well as seasonal albedo changes. However, the present observations, performed in Syrtis Major early spring, indicate that a color change did occur with respect to earlier observations, performed in Syrtis Major late spring and early summer. The apparent color change in 1969 was in such a direction to suggest a higher contrast between Syrtis Major and Arabia in the red and near-infrared than at shorter wavelengths. In other words, in the aeolian hypothesis, the fine-grained bright area material would have been swept cleaner from Syrtis Major in 1969 than previously observed. Nevertheless, it is difficult to separate the effects of season, secular changes, and phase function, so any conclusion about the cause of observed color changes in Syrtis Major and/or Arabia must remain tentative.

Particle size modulation is not the only hypothesis for explaining differences between dark and bright areas. McCord and Adams (1969) have suggested that varying degrees of oxidation in silicates may be responsible. Adams (1968) had matched the integral reflectivity curve for Mars with oxidized basalts, and the 1.00-1.05μ minimum in the spectrum of Syrtis

Major with respect to Arabia suggests important differences in the two surface materials (McCord and Adams, 1969).

In any case, it now appears a new datum can be added to the individuality of the optical properties of Syrtis Major: its pronounced opposition effect. Both its albedo and opposition effect seem to mimic closely the lunar case, but its 1.00-1.05μ absorption minimum is displaced appreciably longward of the 0.90-0.95μ minimum reported for various areas on the Moon (e.g., McCord and Johnson, 1970; O'Leary and Briggs, 1970). It is possible that the particle sizes on Arabia may be sufficiently small to wipe out the 1.00-1.05μ feature which is evident in Syrtis Major. O'Leary and Briggs (1970) measured similar phenomena in the 0.90-0.95μ feature in Apollo 11 samples; some rock samples showed a minimum of $\sim 20\%$ as compared to a $\lesssim 3\%$ minimum for the fine-grained material.

In order to understand the cause of physical differences between bright and dark areas on Mars, we urge that laboratory measurements be made of the opposition effects of oxidized basalts, varying both particle size and state of oxidation. Moreover, further observations of Mars are needed to verify our suggestion of the pronounced opposition effect of Syrtis Major.

Our final comment is with regard to the influence of aerosols and clouds on the Martian opposition effect. O'Leary (1967b), O'Leary and Rea (1968), and Mead (1970) suggested that atmospheric aerosols, whose scattering intensities are most pronounced in the blue and ultraviolet, may account for the observation that the onset of a pronounced opposition effect in only those colors occurred at larger phase angles ($\alpha \gtrsim 6^\circ$). Unfortunately the 1969 observations were performed only at $\alpha < 3^\circ\!.5$, so it is not possible to either corroborate or deny the aerosol hypothesis.

ACKNOWLEDGEMENTS

This work was performed under NASA Grants NGR-33-010-082, NGL-33-010-005, and NAS9-8018. We thank the Cerro Tololo staff for their help in setting up the observations and for the use of their facilities. We also thank the Kitt Peak staff for the loan of their S-1 photometer.

TABLE I

FILTERS USED FOR THE OBSERVATIONS

Full Disc Studies

Filter	Wavelength (Microns)	Bandwidth (Microns)
B	0.45	0.01
V	0.55	0.01
R	0.70	0.01
I"	1.2	0.05

Small Area Studies

1	0.80	0.01
2	0.90	0.01
3	0.95	0.01
4	1.00	0.01
5	1.05	0.02
6	1.10	0.02
7	1.15	0.02

TABLE II

ROTATION MAGNITUDE DIFFERENCE BETWEEN

TWO SELECTED MARTIAN LONGITUDES

Reference	D_E	$\Delta V = V(\lambda_c = 180^\circ) - V(\lambda_c = 270^\circ)$
Lau (1914)[a]	$+10^\circ$	0.11
de Vaucouleurs (1939)[a]	-9°	0.15
Flagstaff (1954)[a]	0°	0.11
Flagstaff (1958)[a]	-11°	0.12
O'Leary and Rea (1968)	$+20^\circ$	0.08
O'Leary and Jackel (1970)	$+7^\circ$	0.13

[a]As presented by de Vaucouleurs (1964).

TABLE III

RANGE IN PHASE ANGLES COVERED

DURING THE OBSERVATIONS

Night (U. T., 1969)	Phase Angles, α
May 31	$1^\circ.45 - 1^\circ.35$
June 1	$1^\circ.35 - 1^\circ.50$
June 3	$2^\circ.50 - 2^\circ.75$
June 4	$3^\circ.30 - 3^\circ.55$

TABLE IV

PHOTOMETRIC PROPERTIES OF MARS FOR FIVE

CENTRAL MERIDIANS NEAR THE 1969 OPPOSITION

Color	Central Meridian, λ_c	Slope of phase curve $dM/d\alpha$ (Mag./deg.)[a]	Zero Phase Magnitude, M(1,0)
B	210	.056 ± .006	- .330
	225	.068 ± .002	- .341
	240	.064 ± .002	- .338
	270	.064 ± .004	- .306
	285	.063 ± .009	- .209
V	210	.052 ± .003	-1.626
	225	.058 ± .006	-1.613
	240	.052 ± .003	-1.581
	270	.055 ± .005	-1.567
	285	.054 ± .006	-1.565
R	210	.038 ± .024	-2.689
	225	.039 ± .005	-2.647
	240	.040 ± .002	-2.621
	270	.046 ± .001	-2.603
	285	.045 ± .018	-2.614
I"	210	.017 ± .007	-2.798
	225	.031 ± .010	-2.783
	240	.024 ± .003	-2.740
	270	.034 ± .002	-2.723
	285	.041 ± .003	-2.753

[a]The slope and probable errors are determined by a linear least squares fit for data between $\alpha = 1\overset{\circ}{.}3$ and $3\overset{\circ}{.}5$.

TABLE V

MEAN PHOTOMETRIC PROPERTIES OF MARS DURING THE
1969 OPPOSITION, COMPARED TO PREVIOUS OBSERVATIONS

	Slope of Phase Curve $dM/d\alpha$ (Mag./deg.)				Zero Phase Magnitude $M(1,0)$		
	B	V	R	I''	B	V	R
Mean (1969)[a], $1\overset{\circ}{.}3 \leq \alpha \leq 3\overset{\circ}{.}5$	.066	.053	.045	.030	-0.33	-1.60	-2.61
Mean (1967), $\alpha = 2^\circ$	~.045	.045	.035	.020(?)	-0.46[b]	-1.73[b]	-2.77[b]
Previous, $\alpha \gtrsim 15^\circ$	.018	.015	.012	.012(?)	-0.19[c]	-1.52[c]	-2.64[c]

[a] Derived as the weighted mean of values from Table IV (see text).

[b] Derived from fitting the opposition effect curve to a linear phase function for $\alpha \gtrsim 15^\circ$. (O'Leary, 1967b, O'Leary and Rea, 1968).

[c] Derived assuming a linear phase function for all α (de Vaucouleurs, 1964).

REFERENCES

Adams, J.B. (1968). Lunar and martian surfaces: petrologic significance of absorption bands in the near-infrared. Science 159, 1453-1454.

Arizona-Tonantzintla Catalogue (1965). Sky and Telescope 30, 24-31.

Barabashev, N.P. (1922). Bestimming der Erdalbedo und des Reflexionsgesetzes für die Oberflache de Mondmeere Theorie der Rillen. Astron. Nachr. 217, 445-452.

Bugaenko, L.A., Koval', I.K., and Morozhenko, A.V. (1967). Comm. To I.A.U. Prague meeting.

Gehrels, T., Coffeen, T., and Owings, D. (1964). Wavelength dependence of polarization III. The lunar surface. Astron. J. 69, 826-852.

Hapke, B.W. (1963). A Theoretical photometric function for the lunar surface. J. Geophys. Res. 68, 4571-4586.

Hardie, R.H. (1962). Photoelectric reductions, In "Astronomical Techniques" (W.A. Hiltner, ed.) Chap. 8, Univ. of Chicago Press, Chicago, Illinois.

Harris, D.L. (1961). Photometry and colorimetry of planets and satellites. In "Planets and Satellites" (G.P. Kuiper and B.M. Middlehurst, eds.), Chap. 8, Univ. of Chicago Press, Chicago, Illinois.

Irvine, W.M., Simon, T., Menzel, D.H., Pikoos, C., and Young, A.T. (1968). Multicolor photoelectric photometry of the brighter planets. III. Observations from Boyden Observatory. Astron. J. 73, 807-828.

Johnson, A.L., Mitchell, R.I., Iriarte, B., and Wisniewski, W.Z. (1966). UBVRIJKL photometry of the bright stars. Comm. Lunar Planet. Lab. 4, 99-109.

McCord, T.B. (1969). Comparison of the reflectivity of bright and dark regions on the surface of Mars. Astrophys. J. 156, 79-86.

McCord, T.B., and Adams, J.B. (1969). Spectral reflectivity of Mars. Science 163, 1058-1060.

McCord, T.B., and Johnson, T.V. (1970). The spectral reflectivity of the lunar surface (0.30 to 2.50μ) and implications for remote mineralogical analysis. Science, in press.

Mead, J.M. (1970). The contributions of atmospheric aerosols to the martian opposition effect. Goddard Space Flight Center X-641-70-13; Icarus, in press.

Oetking, P. (1966). Photometric studies of diffusely reflecting surfaces with applications to the brightness of the Moon. J. Geophys. Res. 71, 2505-2513.

O'Leary, B.T. (1967a). The opposition effect of Mars. Astrophys. J. 149, L147-L149.

O'Leary, B.T. (1967b). Mars: Visible and near infrared studies and the composition of the surface, Ph.D. Thesis, Department of Astronomy, University of California, Berkeley.

O'Leary, B.T., and Briggs, F. (1970). Optical properties of Apollo 11 Moon samples. J. Geophys. Res., in press.

O'Leary, B.T., Rea, D.G. (1968). The opposition effect of Mars and its implications. Icarus 9, 405-428.

Pollack, J.B., and Sagan, C. (1967). An analysis of Martian photometry and polarimetry. Smithsonian Astrophys. Obs. Spec. Rept. 258.

Rea, D.G. (1964). The darkening wave on Mars. Nature 201, 1014-1015.

Sagan, C., and Pollack, J.B. (1966). An inorganic model of Martian phenomena. Astron. J. 71, 178.

Salisbury, J.W., and Hunt, G.R. (1968). Martian surface materials: effect of particle size on spectral behavior. Science 161, 365-366.

van Diggelen, J. (1965). The radiance of lunar objects near opposition. Planetary Space Sci. 13, 271-279.

de Vaucouleurs, G. (1964). Geometric and photometric parameters of the terrestrial planets. Icarus 3, 187-235.

de Vaucouleurs, G. (1968). On the opposition effect of Mars. Icarus 9, 598-599.

Wildey, R.L., and Pohn, H.A. (1964). Detailed photoelectric photometry of the Moon. Astron. J. 69, 619-634.

Younkin, R.L. (1966). A search for limonite near-infrared spectral features on Mars. Astrophys. J. 144, 809-818.

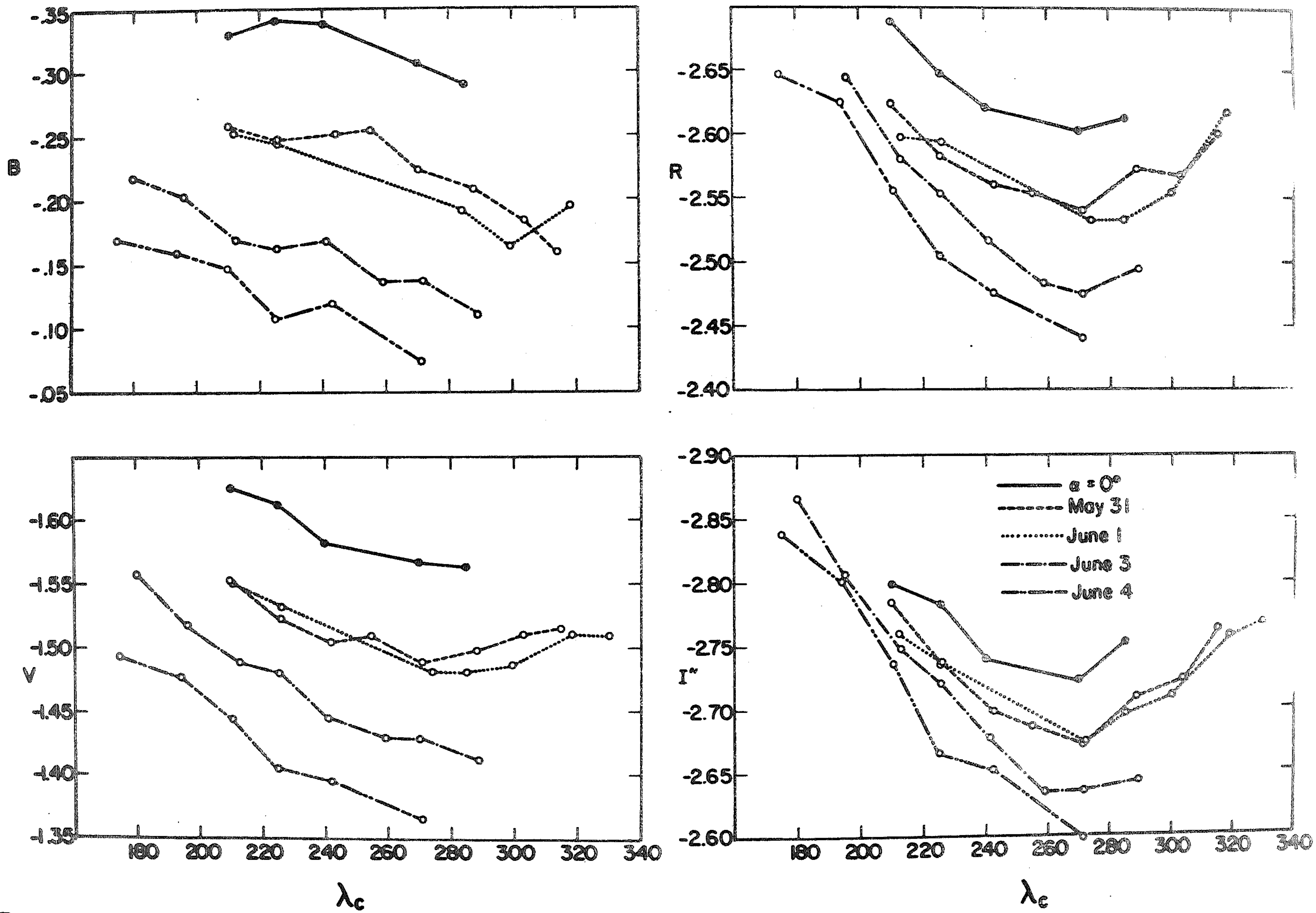
FIGURE CAPTIONS

Fig. 1. Martian magnitude versus central meridian during four nights of observation, 1969. See text and tables for further explanation.

Fig. 2. Scans across the Martian disc with a one arc-second diaphragm. The scans were set to pass through Arabia and the darkest portion of Syrtis Major. Reflectivities are normalized to Arabia values estimated from previous observations.

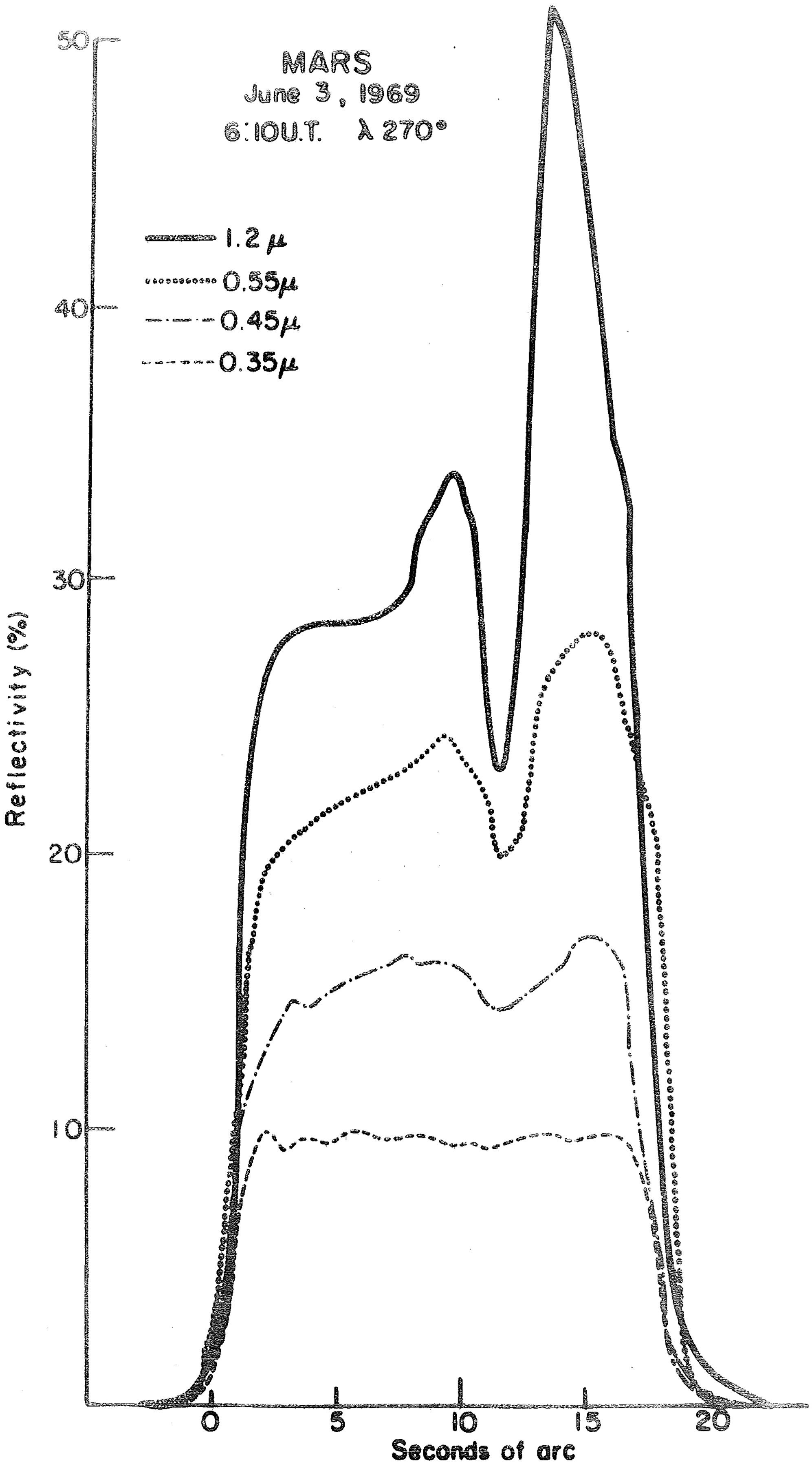
Fig. 3. Same as Fig. 2, except phase angle rather than wavelength is varied. Note the greater contrast between Syrtis Major and Arabia on June 3 ($\alpha = 2\overset{\circ}{.}77$) than May 31 ($\alpha = 1\overset{\circ}{.}35$) or June 1 ($\alpha = 1\overset{\circ}{.}50$), suggesting a greater opposition effect for Syrtis Major.

Fig. 4. Ratios, $1/R_\lambda$, of the intensities of Syrtis Major/Arabia versus wavelength. Younkin's values are plotted for comparison. Note the greater contrast between Syrtis Major and Arabia at the larger phase angle, again suggesting greater opposition effect for Syrtis Major than for Arabia.



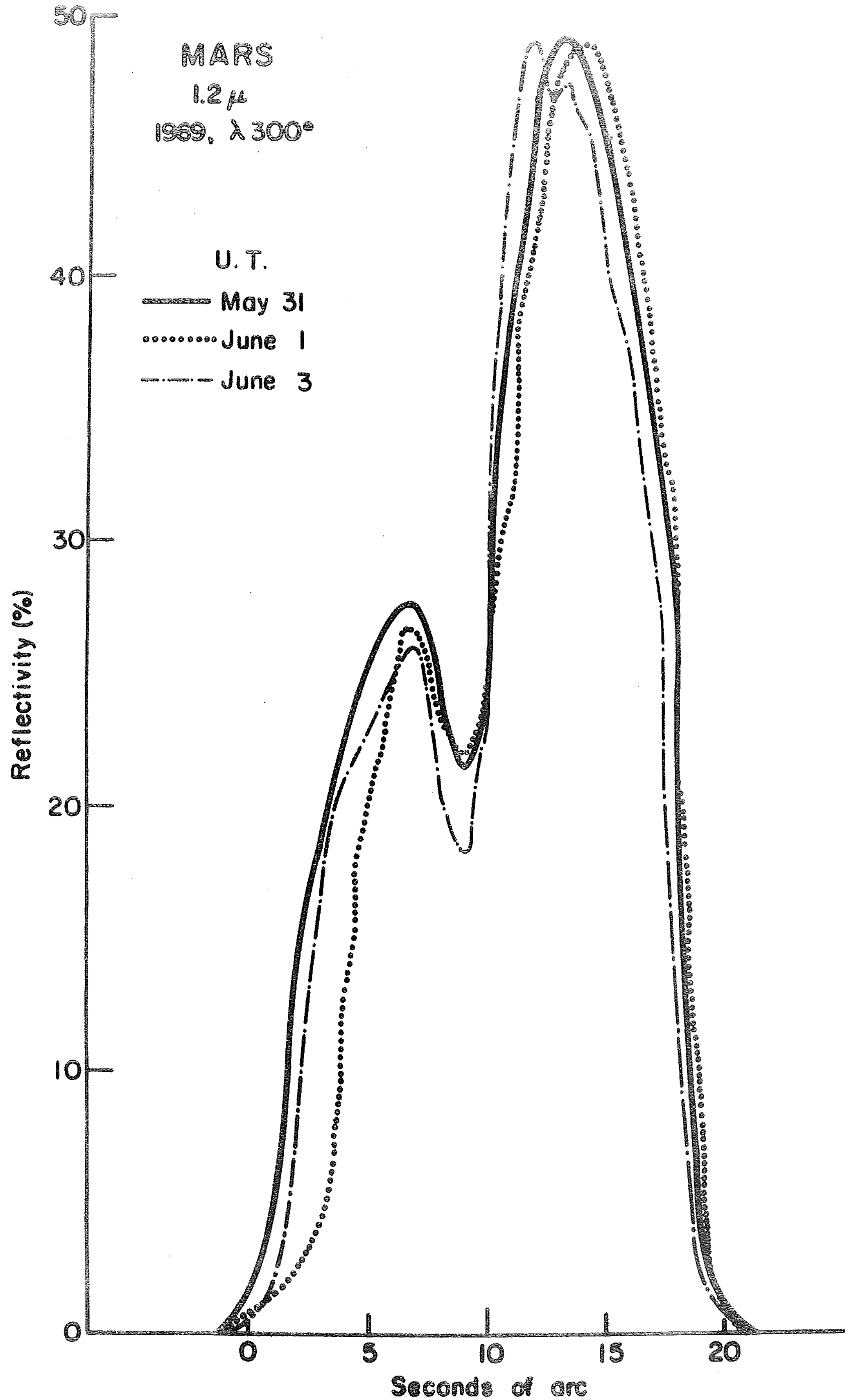
-.35
-.30
-.25
-.20
-.15
-.10
-.05
B
-2.65
-2.60
-2.55
-2.50
-2.45
-2.40
R
-1.60
-1.55
-1.50
-1.45
-1.40
-1.35
V
180
200
220
240
260
280
300
320
340
λ_c
-2.90
-2.85
-2.80
-2.75
-2.70
-2.65
-2.60
I″
α = 0°
May 31
June 1
June 3
June 4
180
200
220
240
260
280
300
320
340
λ_c

Figure 1.



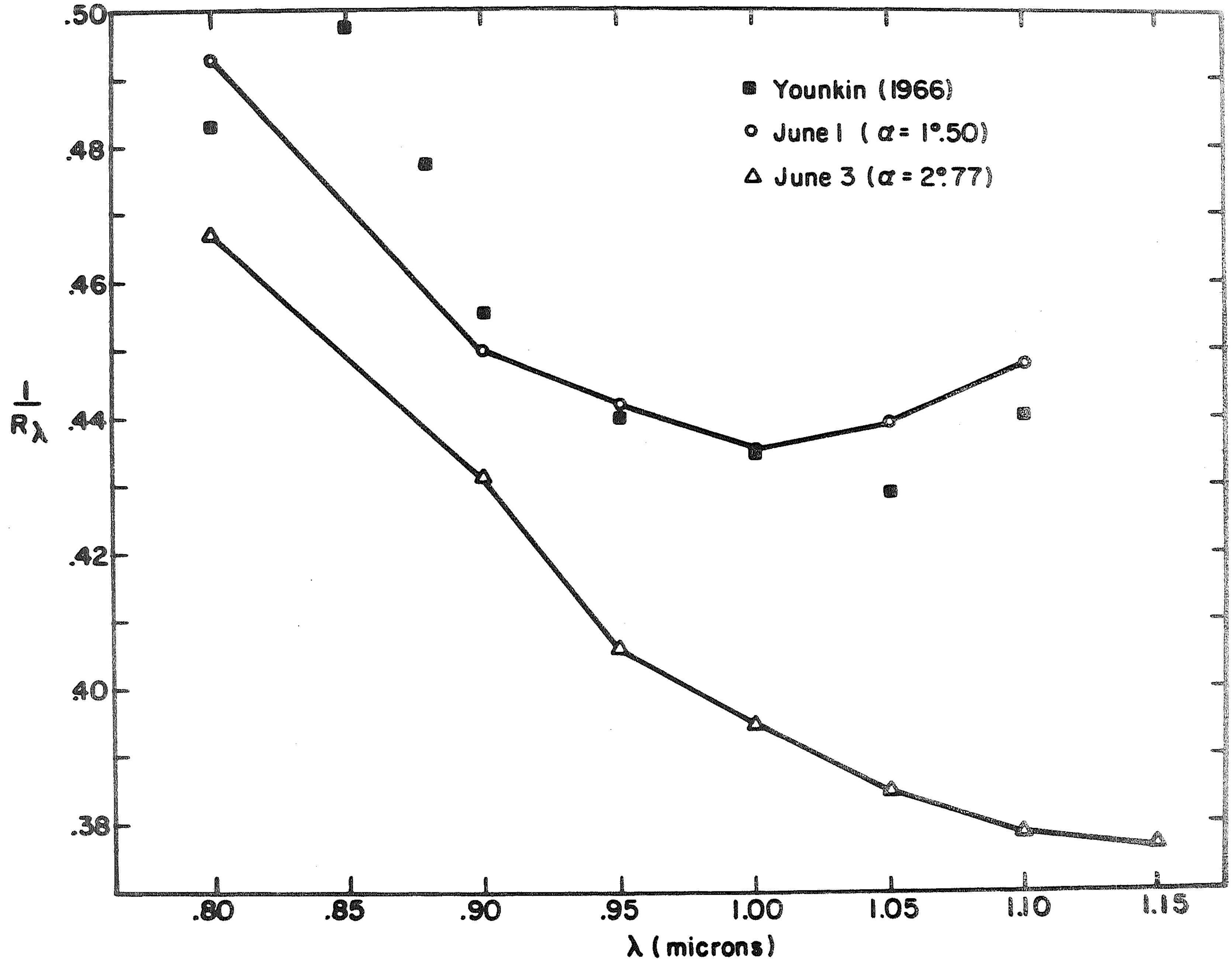
MARS
June 3, 1969
6:10U.T. λ 270°
1.2 μ
0.55μ
0.45μ
0.35μ
Reflectivity (%)
Seconds of arc
50
40
30
20
10
0
5
10
15
20

Figure 2.



MARS
1.2 μ
1969, λ 300°
U. T.
May 31
June 1
June 3
Reflectivity (%)
Seconds of arc
50
40
30
20
10
0
0
5
10
15
20

Figure 3



Younkin (1966)
June 1 (α = 1°.50)
June 3 (α = 2°.77)
.50
.48
.46
.44
.42
.40
.38
$\frac{1}{R_\lambda}$
.80
.85
.90
.95
1.00
1.05
1.10
1.15
λ (microns)

Figure 4.