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THE ATMOSPHERE AND SURFACE OF MARS

A SELECTIVE REVIEW

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by

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ABSTRACT

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Recent significant developments in our knowledge and understanding of the Martian atmosphere and surface are reviewed. With only one or two exceptions the work examined is already in the literature.

The surface pressure estimates using different techniques are roughly as follows: near infrared spectroscopy, 3 - 90 mb; ultraviolet albedo and spectrum, 3 - 30 mb. The atmospheric abundances are: CO_2, 45 m atmo; H_2O, 14 μ precipitable H_2O, variable in time and space; no others detected. Of the latter two of the most important are O_2 and O_3, whose upper limits are 2 cm atm and 4 μ atm respectively. The atmosphere probably contains a semi-permanent load of sub-micron particles (CO_2 or H_2O crystals, or dust) giving the "blue haze". The blue and white clouds are attributed to ice or CO_2 particles.

The surface is characterized by bright and dark areas. The former are covered with dust which is evidently a weathering product of the dark areas. The color is attributed to the ferric ion, but its concentration relative to silicon need not be higher than the relative solar abundance. Dust storms originate in the bright areas, indicating that the local winds at an altitude of 1 meter are higher than 145 km hr^{-1}, and may be as high as 300 km hr^{-1}, or higher.

The dark areas consist of maria, oases, and canals. The biological model for explaining their seasonal and secular changes is not favored, but non-biological interpretations are preferred. It is suggested that the maria are extensive deposits of volcanic ash, the oases impact craters of small asteroids, and the canals loci of small volcanoes oriented along crustal cracks connecting the oases with themselves and with the volcanoes.

Author

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I. INTRODUCTION

Our knowledge of the Martian environment has been growing at an ever increasing pace the past few years. This is directly related to the major space programs initiated by the United States and the Soviet Union. The plans for observing Mars from fly-bys, orbiters, and landers have stimulated not only spacecraft experimental development but also ground-based observations. These have utilized traditional astronomical telescopes, in some instances applying recent technological advances, together with the newer radio telescopes. Complementing the planetary observations have been laboratory studies aimed at facilitating their interpretation. While the major space programs are essentially localized in only two countries, their stimulus has extended to many others and significant contributions are coming from scientists in many lands. It is my purpose today to gather together the published reports of this work and construct a framework to which the subsequent papers can be related. In doing so I will attempt to present a unified picture, but including more than one interpretation for the same phenomenon where the correct one is not clearly indicated. Older data and interpretations, where no longer valid, will be mentioned at most only in passing. Anyone interested in pursuing the historical background further should consult the excellent book by de Vaucouleurs[1]. Another fascinating, but less general work is "Mars, The Photographic Story", by Slipher[2].

Some important characteristics are summarized in Table 1. The mass has been determined by measuring the orbits of the two satellites, Phobos and Deimos. Both are very small and their diameters have perforce been derived from their observed brightness, assuming their reflecting power to be identical to the parent planet. The values so found are 23 - 30 and 11 - 14 km respectively. Their orbital radii are respectively 9,340 and 23,500 km, and Phobos is distinguished among the planetary satellites by having its orbital period, 7 hours 39 minutes, shorter than the rotational period of the parent. Phobos has also been singled out for attention as a possibly artificial satellite since its orbital elements appear to indicate a secular acceleration[3]. This was attributed by Shklovsky[4] to atmospheric drag, whose effectiveness is enhanced by a very low density associated with a hollow structure put in orbit by intelligent Martians. This proposal conflicts with the widespread belief that a highly intelligent and technological Martian life has never developed. Other explanations proposed for the secular acceleration of Phobos are tidal effects[5] and conventional atmospheric drag[6]. The latter explanation used an atmospheric model with a surface pressure of 85 mb, roughly an order of magnitude higher than our best current estimates. This suggests that the drag theory is probably no longer tenable. The writers on this subject have all recognized the inadequacy of the raw data, and have suggested that the effect itself may be fictitious.

The diameters, equatorial and polar, of Mars have been measured by several observers with somewhat discordant results. The most recent determinations, by Dollfus[7] using a birefringent micrometer, give $D_{eq} = 6790$ km and $D_{pol} = 6710$ km, the optical flattening, $(D_{eq} - D_{pol})/D_{eq}$, then being .0117. He observed no difference in diameters for red and blue light, in contrast with some previous workers, notably W. H. Wright, who obtained diameters in the blue which were 2 - 3% greater than in the red. The difference may be due to greater limb darkening in the red, or to a blue scattering haze layer in the atmosphere.

The optical flattening of .012 is significantly different from the value of .0051 obtained by an analysis of the satellite orbits. MacDonald[8] has argued that .012 is improbably high for reasonable strengths of the Martian rocks. The possibility that an atmospheric effect is responsible has been advanced by Kuiper[9], who proposed an equatorial haze layer at an altitude of ca 17 km. This idea has been criticized by de Vaucouleurs[1] on two counts: 1) the maximum altitude of the haze layer is 17 km, at the estimated tropopause, whereas a layer at 70 km is required to account for the difference, and 2) a haze layer can not affect the flattening measured by Wright's method of following surface features as they cross the disc. Moreover the haze layer should have a greater effect in the blue than in the red, whereas the oblateness is not found to be wavelength dependent. Another possible explanation is that the optical flattening is real, and that the density of the material in the equatorial bulge is lower than that in the polar regions[7].

The orbital parameters differ somewhat from Earth's. The mean distance from the Sun is 228×10^6 km, compared to 150×10^6 km for Earth, resulting in a mean solar constant at Mars which is 0.43 that at Earth. In the course of a Martian year of 687 Earth days the planet travels an elliptic orbit with an aphelion of 248×10^6 km and a perihelion of 208×10^6 km. The seasons are accordingly unequal in length, and, since the tilt of the rotational axis is such that summer in the southern hemisphere occurs near perihelion, this season is shorter and hotter than summer in the northern hemisphere. The seasons however are essentially similar to ours since the inclinations of the rotational axes of Mars and Earth to their respective orbital planes are nearly identical.

II THE ATMOSPHERE

A. Pressure

Early estimates of the surface pressure were drawn principally from photometric and polarization observations. Thus the brightness and polarization were measured as a function of wavelength, position on the disc, and phase angle. Certain assumptions were made about the composition of the atmosphere and the reflecting properties of the surface, and the atmospheric pressure was then derived. A set of such values is given in Table 2 taken from de Vaucouleurs[1], p. 124 (the comments in the column "Remarks" are his). After evaluating the various attempts he decided that the pressure was 85 ± 4 mb. This was the value in general use until 1963 when a new and powerful technique, based on infrared spectroscopy, was applied to the problem.

On the night of April 12/13, 1963, a high resolution near infrared spectrogram of Mars was obtained by Spinrad on the 100 inch coudé spectrograph at Mt. Wilson. He was attempting to detect Martian water vapor, and was successful in that quest. But the plate surprisingly showed lines of the $5\nu_3$ band of CO_2 at 8700 A, figure 1. Since the lines were very weak their equivalent width was affected only slightly by the pressure and a CO_2 abundance, essentially independent of the pressure, could be derived. This was done in an analysis by Kaplan, Münch and Spinrad[10] and a value of 55 ± 20 m atmo. found. This abundance was then used to obtain a pressure from the pressure-sensitive 2 μ bands of CO_2 as measured previously by Kuiper and by Sinton, figure 2. The resultant 25 ± 15 mb was much lower than the previously accepted value of 85 mb and created quite a stir, not only in the scientific community, but also in that part of the NASA charged with landing a laboratory on the surface of Mars. When the pressure is so low a significant fraction of a lander's weight is consumed by the spacecraft which must have a large drag coefficient to slow it down so that a parachute can be deployed for a soft landing. Since the engineers would of necessity be conservative in their design, it was mandatory to confirm this new estimate and to reduce its error limits if at all possible.

The desirability of refining the pressure determination is dramatized in figure 3, kindly supplied by C. F. Campen and J. A. Stallkamp[11]. The weights apply to a particular landed capsule designed to operate with uncontrolled entry orientation, for entry angles from grazing (20°) to vertical (90°), and with a single subsonic parachute for terminal descent. The useful landed payload includes power, communications, structures, and scientific instruments (ca 5 - 10% of the useful landed payload). A more precise knowledge of the atmosphere will also permit an orbit to be chosen which has a periapsis closely matched to the actual atmospheric structure and the desired apoapsis and lifetime, Table 3. This clearly facilitates the reconnaissance function of the orbiter, by increasing the spatial resolution attainable.

Accordingly, for scientific and agency reasons, several groups initiated programs to confirm and refine the spectroscopic pressure determination. These efforts have been critically reviewed by Chamberlain and Hunten[12] and by Cann, Davies, Greenspan and Owen[13]. The latter have made some small corrections and have re-evaluated the uncertainties with the results shown in Table 4. Both groups have re-examined the polarimetric pressure determination and have pointed out the numerous critical assumptions in the deductive chain leading from the observational data to the calculated pressure. They are in essential agreement with Dollfus' comment in his original work that his pressure is only "an order of magnitude estimate".

Low pressures have also been derived by Musman[14] and Evans[15] from Martian ultraviolet albedoes. Musman used an albedo for the total disc obtained photoelectrically by de Vaucouleurs. For a phase angle of 21° and $\lambda = 3300$ A an albedo of 0.032 was found. Assuming that (1) there are no particles in the atmosphere contributing to the albedo, (2) there are no absorbing atmospheric constituents, and (3) the surface reflectivity is zero, Musman calculated surface pressures of 27 mb for a pure N_2 atmosphere and 19 mb for a pure CO_2 atmosphere.

Evans has used an Aerobee rocket to obtain an ultraviolet spectrum between 2400 and 3500 A, figure 4. In deriving a pressure he makes the following assumptions: 1) the surface reflectivity is 1% at 3000 A and 0 at 2500 A, 2) there is a haze due to 0.2 μ diameter ice spheres which reflects 2% at 3000 A and 2.5% at 2500 A, and 3) the various reflectivities add. The results are 6 ± 3 mb for pure CO_2, 9 ± 4 mb for pure N_2, and 13 ± 6 mb for pure A atmospheres. There is no evidence for band structure in the spectrum as one would expect if gaseous absorbers were present. If there is atmospheric absorption in this region it would have to be continuous, and probably due to suspended solids. Actually the similarity of the spectrum to that expected from a pure Rayleigh scattering atmosphere suggests strongly that atmospheric absorption, if present, is very slight. This point is reinforced by the close agreement between his results and the most recent ones obtained by the spectroscopic and occultation techniques.

The best pressure estimates, as available in the literature prior to this meeting, are gathered in Table 5.

B. Composition

The first molecule to be identified in the Martian atmosphere was CO_2. Kuiper[9] noted that the 1.575 and 1.605 μ CO_2 bands were stronger in Martian spectra than could be accounted for by the telluric CO_2. Early estimates of the abundance were based on the atmospheric pressure of ca 90 mb, and have now been superseded by abundances based on the $5\nu_3$ band. The initial value of 55 ± 20 m atmo. of Kaplan, Münch, and Spinrad[10] has been revised by Cann et al[13] to 43 ± 24 m atm. The latter authors have re-analyzed a determination by Owen and arrived at 46 ± 20 m atm. It is repeatedly stressed by the workers in this area that all of the CO_2 abundance measurements, and accordingly the pressure determinations, are based on only one plate of the $5\nu_3$ band of Martian CO_2. This situation has been rectified and additional measurements of the Martian band will be reported later today. Parenthetically it might be noted that 45 m atm. of CO_2 corresponds to a partial pressure at the surface of 3.3 mb.

The only other molecule yet detected in the gas phase is H_2O. The detection of water vapor is credited to Spinrad, Münch, and Kaplan[16] who used the Doppler shift, produced by the high relative velocity of Mars with respect to Earth at quadrature, to shift the Martian lines onto the wings of the much stronger telluric lines, figure 5. An analysis of the line intensities gave an abundance of 14 ± 7 μ precipitable water, averaged over the entire planet. This is not very much and, if present in a constant mixing ratio in the atmosphere, would give relative humidities at the surface of 8.5×10^{-5} and 1.4×10^{-5} at 273 and 300° K respectively, and a dew point of -80° C. As might be expected the water vapor abundance is not constant, but varies both in time and space. Observations of these variations will be presented by H. Spinrad this afternoon.

As for other possible atmospheric constituents only upper limits are available. A proposal that the oxides of nitrogen system could explain several Martian phenomena[17] has provoked a certain amount of debate, and attempts have been made to confirm the initial work. These have failed, but they have served to decrease the upper limit on the NO_2 abundance to ca 0.01 mm atmo[18, 19]. This is far below the level necessary to produce the phenomena postulated by Kiess et al, so that their proposal must be rejected.

A pair of molecules whose upper limits have also been recently reduced are O_2 and O_3[15]. Evans has set an upper limit on O_3 of 4μ atm. Using photochemical equilibrium calculations of Marmo and Warneck he then derives an upper limit for O_2 of 2 cm atm. This is considerably lower than the 70 cm atm. estimated by Kaplan et al[10] from the absence of Doppler shifted Martian lines in the 7600 A band of O_2.

Another compound which has been the center of some speculation is acetaldehyde, proposed by Colthup[20] to explain certain features of the infrared spectrum. In the subsequent section on the Martian surface the spectral evidence will be discussed and it will be noted that there is no evidence for ascribing absorption at acetaldehyde frequencies to the Martian atmosphere. This implies an upper limit on this molecule of ca 60 μ atm[21].

Kuiper[22] has continued his near infrared spectrometic studies and determined the following upper limits: CO, < 1 cm atm; CH_4, < 1 mm atm; NH_3, < 1 mm atm; N_2O, < .8 mm atm; NO, < 20 cm atm; H_2S, < 7.5 cm atm; H_2CO, < 0.3 cm atm; COS, < 0.2 cm atm. Moreover he has tentatively determined an $0^{18}/0^{16}$ ratio "larger" than on Earth and is currently making a precise determination.

The abundances of the various detected and considered components are listed in Table 6. Two molecules, N_2 and A, are missing from the table, although they have been used frequently to make up the discrepancy between the partial pressure of CO_2 and the estimated total pressure. In view of the current state of flux of estimates of these two quantities it seems preferable to omit them from the table, and simply state that they are likely candidates for any difference which may exist.

C. "Permanent" Particulate Content

The existence of a more-or-less permanent load of particles in the atmosphere has been suspected as the cause of the lack of contrast in blue pictures, figure 6. The most likely prospects for the aerosols are ice or carbon dioxide crystals, or dust particles, with diameters in the sub-micron region. Recently Kuiper[22] has briefly re-examined the problem, nothing the unusual polarization effects observed by Gehrels at $\lambda = 3200$ A. For instance, over a 7-day period at a phase angle of $43^\circ.3$ the polarization changed from 1.5% to 9.8%, evidently reflecting a change in the particle size distribution. Kuiper has examined Gehrels' data in conjunction with calculations based on Mie scattering theory and believes that the data favor sub-micron ice spheres. He stresses that this is only tentative and that extensive photometric and polarization observations at ca 3200 A are very desirable. This wavelength is particularly appropriate since the surface reflectivity is low and the Rayleigh scattering by the atmosphere has not begun to dominate. Moreover it is accessible from Earth-based observatories, a very convenient circumstance.

It should be noted that the increased amount of CO_2 now estimated on Mars increases the probability that the particles are composed of CO_2. I know of no observational data which exclude CO_2, and a simple calculation indicates that crystallization of CO_2 at altitudes of ca 20 km is not improbable[23]. If the particles are ice crystals then there should be a correlation between the blue clearings and the amount of water vapor in the atmosphere. The latter apparently varies widely so that this correlation should be quite apparent. If one does not exist then the possibilities can be narrowed to CO_2 crystals or dust particles.

D. Clouds

Three types of clouds have been discussed -- blue, white, and yellow[1, 2]. The latter, almost certainly due to dust storms, will be discussed in the Surface section. The blue clouds are evident as bright spots on blue pictures, but are not seen on pictures in the red, while white clouds are visible throughout the visible. There seems little doubt that the two are related, and are clouds of crystalline H_2O or CO_2. A recent survey[24] suggests that white clouds occur most frequently over bright areas and adjacent to dark areas. Wells has proposed that these are analogous to clouds produced on Earth where moisture laden winds blow at right angles over a mountain range. Down wind of the range there are regions where the air is at a low pressure, and the adiabatic expansion cools it sufficiently to permit condensation. If this is occurring on Mars it implies that at least some of the dark areas are elevated, and that the winds blow from the dark to the bright areas during the time when the clouds are observed.

III. SURFACE

A. Principal Observations

The visual appearance of the planet[1, 2] presents areas that are bright ochre, dark, and white, figure 7, with the bright areas concentrated in the northern hemisphere, the dark areas in the southern hemisphere, and the white areas near the poles.

a) The white areas at the poles

When winter occurs in a particular hemisphere a white shroud forms about its pole, and extends to cover a significant portion of the hemisphere. In southern winter the white cap extends to ca 42° S and in the northern winter the corresponding cap goes to ca 57°N. As a result of polarization studies by Dollfus, infrared spectral work of Kuiper (confirmed by Moroz[33]) and considerations based on the local temperature and the partial pressure of gaseous constituents over it, the caps are now believed to be a thin (ca 1 mm) coating of finely divided ice crystals, similar to hoar frost. They wax and wane with the seasons in a manner completely analogous to our own snow caps.

b) The bright areas

The hue of the bright areas is generally accepted to be reddish or ochre, and is close to that observed by the naked eye for the integrated planetary light. Its spectrum, figure 8, merely confirms this fact. Not all areas are equally bright, with Hellas being the brightest. Hellas is distinguished by being the southern most extension of the south polar cap, and is at times very bright, suggesting it is temporarily covered with a deposit (frost?). It has been concluded that it must then be an elevated plateau[27], and is thus one of two areas to which an increased or decreased elevation can be assigned with some degree of certainty. The other is the

Mountains of Mitchel which manifest themselves as isolated white spots when the south polar cap recedes.

Polarization observations have been carried out by Dollfus[28] for the range of accessible phase angles and for the various seasons. No seasonal variation was observed but a highly characteristic dependence on the phase angle was discovered, figure 9.

The material covering the bright areas is evidently fine dust since dust storms of the same color are frequently observed. They may be localized in extent, or cover a major fraction of the planet, figure 10. Ryan[29] has made a detailed study of some of the problems associated with dust on Mars: 1) the winds necessary to raise dust off the surface, 2) the vertical winds required to elevate the dust into the atmosphere, and 3) the settling time for particles of different sizes. A calculation of particular interest to engineers designing Martian landers is the range of surface wind velocities which may be encountered. For a 25 mb pressure and a model surface which is probably most applicable to Mars the minimum winds estimated to initiate grain motion are 145 - 190 km hr^{-1} at an altitude of 1 meter, and 230 - 270 km hr^{-1} at an altitude of 100 meters. These velocities will scale roughly as pressure$^{-1/2}$, so that for a pressure of 10 mb they are ca 230 - 300 km hr^{-1} and 360 - 430 respectively, and for a pressure of 5 mb ca 320 - 420 km hr^{-1} and 510 - 600 km hr^{-1}. These are all much higher than the winds of up to 100 km hr^{-1} deduced from the cloud movements. Assuming the surface model is reasonable the only explanation is one proposed by Ryan wherein "...the clouds are initiated in transient cyclonic systems".

Temperatures have been measured from the emitted infrared radiation by Lampland (data reduced by Gifford[30]), Pettit and Nicholson[31], and Sinton and Strong[32]. Maps have been produced by Gifford showing the variation of the noon time temperatures as a function of latitude, longitude, and season, figure 11. The diurnal variation has been measured most precisely by Sinton and Strong, figure 12, who deduced therefrom a thermal inertia, $(k \rho c)^{1/2}$, of 0.004. This is comparable to values observed for dry, finely divided, uncompacted samples of dust. In calculating the thermal inertia the effects of the atmosphere were considered in a semi-quantitative fashion. While a more precise consideration of heat exchange between it and the surface via radiation and conduction will change the derived value, it would be surprising if the general conclusion were altered.

c) The dark areas

The dark areas are probably the most fascinating of the many Martian enigmas, since their appearance and behavior have stimulated many scientists to propose there is life on Mars. They consist of three distinct classes -- maria, e.g. Syrtis Major, canals, and oases*, where several canals may intersect, figure 13. When seeing conditions are good the maria are split up into collections of dark nuclei on a lighter background[25], and the canals are resolved into disconnected areas more-or-less aligned, e.g. cf. Focas[33] and Dollfus[34]. The intricate system of over 400 canals described by Percival Lowell has not withstood the test of time, but a complex system of disconnected aligned dark spots has taken its place, figure 14. It should be noted that the connecting lines lie close to or on great circles, that several may intersect at an oasis, and that they commonly connect oases with nearby oases and with the "tips" of the extended areas.

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*This is a convenient designation although nobody today believes there are Martian areas similar to our seas, canals, and oases.

The colors of the dark areas have been debated at considerable length. Visual observers have cited almost the entire spectrum, from red to blue. However there has been no objective confirmation of many of these, and the only shade recorded spectrographically is one which is reddish, but less so than the bright areas, figure 8. The visually reported colors have been ascribed to bad seeing[35] and to a contrast effect with the adjacent bright, and more reddish bright areas. Until positive evidence to the contrary is produced I prefer to ignore the reportings of blues and greens, which have been used to form a part of the case for life on Mars.

Polarization studies have been equally fruitful in examining the dark areas as the bright areas. Just as for the latter the polarization vs. phase angle has a distinctive appearance, figure 15. A provocative seasonal effect which was discovered will be discussed in the following paragraph on the darkening wave.

As the season in a particular hemisphere changes from winter to spring the polar cap recedes. As it begins to do so the dark areas adjacent to the cap become darker. As the season progresses the darkening moves towards the equator and ultimately crosses it. Behind this darkening front is a brightening front, so that there appears to be a wave of darkening moving along the planet, figure 16[28, 33]. Associated with the decrease in brightness is a change in the polarization, with the negative branch becoming more pronounced and the inversion point shifting to higher angles, figure 15.

Not only is there a seasonal change in the appearance of the dark areas, but secular changes also occur, figure 17. Two regions where such changes have been particularly marked over the past several decades are Solis Lacus, and the Thoth-Nepenthes canal system.

A promising means of studying a surface is to observe its infrared spectrum, in the hope of detecting vibrational bands which will be indicative of the composition. This approach was taken by Sinton[36] when he obtained spectra in the 3 - 4 μ region, figure 18. His initial observations were that minima existed at 3.43, 3.56, and 3.67 μ, that they were more pronounced for the dark areas, and that they strongly suggested the presence of organic matter thereon. As noted earlier Colthup[20] believed that one band, that at 3.67 μ, may be due to acetaldehyde. However after a critical re-examination of the data it has been concluded that the bands at 3.56 and 3.67 μ are almost certainly due to HDO in our own atmosphere[37], figure 19. The band at 3.43 μ has not been questioned, but it requires confirmation, especially since it is on the shoulder of a strong telluric CH_4 band. Moroz[38] has also reported a minimum at 3.43 μ, together with others at 3.53, 3.59, and 3.69 μ. The reported resolution of the features at 3.53 and 3.59 μ conflicts with his stated spectral band width of .09 μ. In view of this discrepancy the confirmation of the 3.43 μ feature should be regarded as only tentative. If it is, in fact, real, it may be due either to surface carbonates or organic material[39].

Temperatures of the dark areas have been found to be somewhat higher than for the bright areas. Specifically, "the maximum temperature at a favorable opposition for a desert area near the equator of the planet appears to be close to 25° C, and for a dark area it is about 8° hotter"[32]. This difference is roughly what one would expect due to the difference in albedoes if the thermal inertia of the dark areas is low, comparable in magnitude to that of the bright areas.

d) Microwave observations

During the opposition of 1963 Jet Propulsion Laboratory scientists observed Mars with their 12.6 cm radar for a total of 65 hours[40]. A spectral analysis of the returned signal, figure 20, showed the signal to be coming predominantly from a small area near the center of the disc, implying the surface is in fact quite smooth. However the data were too noisy to justify any attempt to quantify the roughness. A plot of signal vs. Martian longitude suggested a higher signal from the Syrtis Major region, but again the noise was too high to enable positive statements to be made.

Passive observations have been carried out by several workers, most recently by Kellermann[41]. At $\lambda = 21$ cm Davies[42] had derived a temperature of 1140 ± 50° K, which presumably would have to arise from radiation belts. This was not confirmed by Kellermann who has reported the temperatures in Table 7. These agree very well with previous data of Giordmaine, Alsop, Townes, and Mayer, and of Drake. Because of the lack of confirmation of the high temperature, and the absence of a magnetic field and radiation belts as determined by Mariner IV, it seems reasonable to reject Davies' result. The data of Kellermann are consistent with a planet where the microwave radiation comes from depths where the temperature is constant, with no diurnal variation. This is equivalent to stating that the microwave temperature is equal to an infrared temperature calculated from the average flux emitted by the entire disc.

e) Mariner IV pictures

The most exciting event for students of Mars has undoubtedly been the flight of Mariner IV and the information it has provided on the planet. This will be discussed in detail on Saturday; for now I will restrict myself to a few remarks on the T. V. experiment[43]. The outstanding point which it has introduced is the large number of craters to terrestrial organisms.

Yagoda[44] has estimated particle fluxes at the surface, but for a pressure of 85 mb. His results must be extensively revised to take account of the low pressures now accepted.

B. Interpretation

In discussing the variety of interpretations put forward for surface phenomena I must of necessity restrict myself to a manageable number. I will then make a critical selection, choosing for examination those that have aroused the greatest controversy or which have the greatest promise. It should be noted that the two categories are not identical.

a) The composition of the bright areas

The spectrum, polarization, and thermal inertia of the bright areas, and the characteristics of the dust clouds have been used in speculating on the composition. It is generally accepted that the latter three properties testify to finely divided material, with grain sizes ranging from 100μ to 1μ. It also must be uncompacted, and since bodies of liquid water have probably been absent for periods up into the billions of years the aeolian erosion must have resulted in large quantities of dust which, in places, may now form a very deep surface covering.

As for the mineralogical composition very little can be said with certitude. A considerable number of observations, both spectral and polarimetric, are in the literature, which also contains some positive conclusions based on these data. However a general criticism may be laid against almost all of this work, since only rarely was the material studied in the laboratory characterized in any but the most general manner. Investigators have examined the spectral and polarimetric properties of a wide range of minerals, but the state of aggregation has seldom been specified. This is distressing since both parameters depend critically on the particle size and the presence or absence of a surface coating. Some observations reported have been made on rock surfaces, a surface which must be rare and may be completely absent in the Martian bright areas. Moreover the mineralogical composition of the samples has never been adequately given. A substance mentioned frequently as the bright material is limonite, but this is one of the most poorly characterized substances in mineralogy. Hovis[45], in his spectral study, has given the most complete description of his samples, Table 8. While it is not complete, e.g. the elemental composition is not given, it serves to demonstrate the range of materials which geologists group under the term "limonite". And his spectra reflect this range in their details. I would like to stress this point of sample characterization, which is important not only for its implications on the Martian surface, but also for checking between terrestrial laboratories. Thus Coulson (cited by Cann et al[13]) attempted to check Dollfus' polarization data on limonite, but failed. This was presumably due to different samples examined by the two investigators.

With this preamble let us look at the materials which have been suggested. The reddish color and the cosmic abundance of iron led the early investigators to propose a highly oxidized surface containing iron in the ferric state. Polarization and unpublished spectral measurements of Dollfus led him to conclude that the material was essentially limonite. However the polarization curve was derived from the observed by subtracting out a component which would be expected for a Rayleigh scattering atmosphere of terrestrial composition and with a surface pressure of 90 mb. This is clearly over corrected in view of our present knowledge of the atmosphere, and moreover, if aerosols are present, the correction can be exactly the opposite[46], figure 23, and a variety of materials can then fit the reduced curve.

The visible and near infrared spectrum was used by Kuiper in arriving at an identification of felsitic rhyolite. However it has been noted that the surface examined was old and may have had a weathered coating of limonite[47]. The spectrum of limonite, cited so commonly, is similar to those of other ferric oxides in exhibiting a minimum at 8750 A, figure 24. The absence of this minimum, or its weakness if present, in the Martian spectrum argues strongly *against* a covering which is pure ferric oxides and their hydrates, a point recognized by Adamcik and his co-workers[48]. They prepared a synthetic mixture of goethite ($Fe_2O_3 \cdot H_2O$), kaolin ($Al_2O_3 \cdot SiO_2 \cdot 2H_2O$) and hematite ($Fe_2O_3$) in the weight ratio 16 : 100 : 16 and added "a few percent" of a black material (magnetite). The resulting spectrum closely resembled Mars'.

This demonstration relieves one of the necessity of postulating mechanisms for producing a spectrum equivalent to "pure" limonite. One such proposed was a surface covering, or paint, on silicate particles[47, 49]. Another was a concentration of the fine, soft limonite particles on the surface resulting from fractionation during settling after dust storms[50]. My personal opinion now is that the bright areas are oxidized, the color is due to the Fe^{+3} ion, and the Fe/Si atom ratio need be little different from the solar value of 1 : 3.5[51].

b) The nature of the dark areas

This is the topic which has generated the greatest heat due to its possible association with a Martian biota. In treating it I will divide it into sections dealing with the biological and non-biological interpretations. Some of the latter invoke life phenomena, but their main features are non-biological.

i) The biological interpretation

This theory reached its culmination in the hands of Lowell, who peopled the planet with intelligent beings capable of constructing an intricate system of irrigation canals. As our knowledge has improved and we have become aware of the desiccated state of the surface and atmosphere, the low atmospheric pressure, the lack of oxygen, and the possibly high radiation flux at the surface, an element of sobriety has entered into the deliberations. Still, one should certainly not exclude the possibility of a Martian biota and, accepting this, it is natural to try to explain some of the observed phenomena on this basis.

The darkening wave moving from the poles towards and across the equator is the most intriguing effect to explain. On a life basis it is handled in the following manner. On Earth organisms have lots of water, so that temperature is the critical factor in their growth. Accordingly a terrestrial darkening wave exists, but moves from the equator towards the poles as the season progresses from winter to summer. On Mars, however, while the temperatures are certainly not benign, it is the availability of water which is critical. When the polar caps begin to sublime and recede the water released moves towards the equator and becomes available to organisms present in the soil. They then proceed to proliferate, darkening the surface and changing its color. Then as the relative humidity decreases due to the passage of the wave of moisture the organisms become dormant and the areas brighten. An attempt by Dollfus to duplicate the polarization behavior by terrestrial organisms failed, but then life has manifold forms and one can always conceive of some hypothetical form which has the desired properties. The secular changes in the dark areas are considered to be the expansion of organisms into a previously barren region, or a regression of them from one previously fertile.

I have been skeptical of this model in the past[52], and have not altered in this respect. The range of non-reddish colors, in particular greens and blues, are doubtful and may well be artifacts introduced by our own atmosphere and our psychological processes. The temperatures prevalent in at least some of the dark areas during the darkening process also argue against an associated biological activity. Thus, Depressio Hellespontica, located at 60 - 65° S latitude, participates prominently in the darkening wave, and yet attains a maximum summer temperature of −23° C, and a temperature at the height of the darkening wave of only −28° C, figure 25. This is a measured brightness temperature and should be raised about 2 - 3° to allow for an emissivity of ca 0.95. There may be a certain experimental error, and there may be localized areas where the albedo is lower and, as a consequence, the temperature higher. Still, the surface temperature will probably never exceed 0° C, even on the hottest day. This seems extraordinarily low to permit a proliferation of life based on water as solvent. It is true that salts, in particular alkali and alkaline earth halides, if present in large concentrations can significantly lower the freezing point of water. Therefore an unequivocal rejection of a biological explanation for the darkening of Depressio Hellespontica cannot be made, but I regard it as highly improbable. It is only natural then to extend this conclusion to other areas participating in the darkening wave, and to conclude that the biological interpretation for the wave itself is improbable.

The secular changes, or at least some of them, also are difficult to explain by biological activity. The area Hellas, normally bright, was dark during the 1954 opposition, but in 1956 returned to its normal appearance. Since it covers an area of 290,000 square miles any organisms which can quickly extend over it to the extent required to change its visual appearance so drastically must be quite unique.

Finally must be mentioned the ability of the dark areas to regain their original appearance after a dust storm. Öpik[53] argued that the only means of accomplishing this was by invoking vegetation which would grow through the dust layer. This is a possibility, and is perhaps the most telling argument for interpreting the dark areas as being vegetation covered.

It should be noted that no terrestrial life forms have been demonstrated to have the requisite hardiness and proliferation to explain the Martian phenomena. Kuiper[9] has suggested lichens as the Martian cover because of their ability to live in very hostile environments, and because of the range of colors they may possess. Salisbury[54] has criticized this proposal, noting that the growth rate of lichens is far less than that required. Not only lichens are hardy, but also certain strains of bacteria, but populating a planetary surface with such organisms to the level required to explain the Martian phenomena seems ludicrous. If a Martian biota is responsible for these visual effects it must have properties quite different from any species with which we are familiar.

Of course, this is only to be expected, since any existing Martian life would have to evolve to fit into the developing ecological niches. Since these are so different from any on Earth the organisms would in all probability be quite unfamiliar.

ii) The non-biological interpretations

In this category I want to single out work by four authors who, in my opinion, have proposed ideas which have considerable merit. They are Tombaugh[55], McLaughlin[27,56], Kuiper[35], and Smoluchowski[57]. I will first describe briefly the salient points of their proposals, and then extract certain ideas and meld them into a description which has the greatest appeal to myself.

Tombaugh suggests the shrinkage of the planet has produced a "tetrahedral deformation" with the maria lower than the bright areas, which he states is in conformity with the evidence available. The oases are depicted as craters formed by the collision of small asteroids, and the radiating canals are cracks in the crust resulting from the impact. The colors and seasonal behaviors are "undoubtedly due to the growth of vegetation" with the "fractured zones", i.e., the canals, giving "haven to a hardy vegetation in regions of unfavorable environment". The mechanism of this is not spelled out, and it is not clear whether he regards the canals as valleys or as the loci of volcanic activity, either of which could provide the necessary haven. The vegetation part of this hypothesis and the idea that the dark areas are depressed I find difficult to accept. Specifically, I know of no good evidence suggesting the dark areas are depressed. It is believed that Hellas is an elevated plateau, but this need not imply that all of the bright areas are elevated. In view of the widespread dust storms it would seem more natural that the low areas would be covered with this dust, and hence would be bright.

In his two papers McLaughlin developed a volcanic model to explain the maria and certain of the canals. The peculiar tendency of the maria to be concentrated near the equator, to have "triangular" or funnel-shaped estuaries, and to trend in a south-east north-west direction suggested to him that they are the result of volcanic action. If, at the point of the funnels there exist volcanoes, the expected prevailing trade winds in the southern summer will blow the ash in just the right direction to explain the extended areas. In northern summer the planet is further from the sun and the counter winds will be much weaker. Rather than produce long dark areas they blow the ash into the thin streams which we see as canals radiating from the volcanic tips. McLaughlin states that the volcanoes all lie close to a great circle inclined at 25° to the equator and likens this to Earth's circum-Pacific volcano belt. However, when the volcano positions are plotted on a stereographic projection it is seen that between 0 - 180° aereographic longitude his statement is valid, but that between 180 - 360° they scatter about the equator, figure 26. The canals are attributed to a variety of possible causes, of which ash deposit from active volcanoes is only one. They may be 1) linear chains of small volcanoes, along major crustal fractures, 2) major fault zones in which the surface irregularities have trapped drifting volcanic ash, 3) rift valleys related to fault zones, or 4) igneous dikes. The seasonal changes may be due to 1) moistening of the surface, or 2) a new fall of ash. Secular changes can arise from an increase or decrease of volcanic activity. The concept that volcanic activity has played, and maybe still plays, a major role in shaping the surface is intriguing, although some of the details are difficult to accept. Continuously active volcanoes required for the seasonal changes are improbable, and the humidity is too low for any moistening of the soil which is more than transient. Explaining some of the canals as ash deposits from a central volcano at an oasis is improbable in view of their narrowness relative to the extended areas, and in view of the fact that in general several canals intersect at any one oasis. The attribution of canals to valleys has already been criticized, and associating them with faults seems unlikely because of their tendency to intersect. Not only do they meet at oases, but they also intersect with no apparent influence on one another's path. This behavior has not been reported for faults on Earth, and certainly appears unusual.

A different proposal was advanced by Kuiper[35] after making extensive visual observations during the 1956 opposition. He suggests the dark areas are lava fields, and that the dust cover is variable, depending on the seasonal winds. Secular changes are the result of secular changes in the wind pattern. The regenerative power is due to the ability of the wind to blow the dust particles off the lava. He believes that some of the reported green colors are valid observations and includes in his model "a partial cover of some very hardy vegetation". He gives no further details of his model, in particular he makes no proposal regarding the relative elevations of the dark and bright areas, nor of the actual behavior of the presumed vegetation.

The possibly high ultraviolet ($\lambda > 2000$ A) flux at the surface prompted Smoluchowski[57] to suggest that UV-produced color centers may explain some of the Martian phenomena. The high flux may produce color centers whose population is temperature dependent. In winter the centers would be depopulated, while in summer they would be populated and the material would be darker. Secular changes could be the result of extraordinarily high irradiation due to photons and corpuscular matter from solar flares. No mineralogical systems were advanced as demonstrating these phenomena, and no effort was made to explain the regenerative property of the dark areas. While the hypothesis is interesting it would seem to predict a wave that moves from equator to pole since this is the direction in which the maximum daily temperature increases, and it is this temperature which presumably is most critical in the kinetics. The observed wave appears to be correlated more with the atmospheric transport of water vapor, a factor not considered in Smoluchowski's treatment.

Finally, I would like to extract some ideas from these works, add one or two of my own, and present a picture that seems most reasonable, at least to myself. It is essentially an extension of some previous ideas[52, 58]. First the dark areas are considered to be elevated, and the bright areas depressed and dust covered. The observation by Sliper[2] of temporary dark areas adjacent to yellow clouds is interpreted simply as areas from which the dust cover has been temporarily removed during the storm. His explanation invoking a wetting of the soil by precipitated water is untenable in view of the dryness of the atmosphere. The maria are probably the deposits of volcanic ash, wind-blown from volcanoes at their vertices. The oases are most likely impact craters and the canals strings of small volcanoes aligned along crustal fractures linking the impact craters with themselves and with the major volcanoes. The possibility that the canals are ejecta thrown out from the primary crater was considered, but was rejected because 1) they would probably require too much material for their formation, and 2) they would not be expected to connect oases and volcanoes to the degree apparent. The darkening wave may be due to 1) small dust particles seasonally transported on and off the dark areas, or to 2) a seasonal darkening of a permanent surface, due perhaps to a reaction with H_2O vapor which is promoted by the high radiation fluxes. The polarization changes may be a result of a change in particle size or of the decrease in brightness. The influence of the latter may be an intrinsic surface effect or a consequence of an increased relative contribution of aerosol scattering[46]. Secular changes may be ascribed to changes in the wind pattern, to volcanic activity, or to both. The regenerative ability results from the settling of the dust into the lower areas. The dark material is essentially unweathered volcanic ash, the bright material the products of its weathering. Even though liquid water is rare, if present at all, a slow weathering may still occur[56], and may in fact be facilitated by the incident energetic radiation.

IV. CONCLUDING REMARKS AND ACKNOWLEDGEMENT

This is a highly selective review. It is intended to illustrate recent important advances in our knowledge, and to provide a critical appraisal of the current theories on the atmosphere and surface. Encyclopedic coverage has not been attempted, and I sincerely hope that no papers of significance for the present purpose have been omitted.

Much of the appraisal has benefitted from collaboration and discussion with several colleagues, notably W. J. Welch, M. Calvin, T. Belsky, B. T. O'Leary and R. A. Wells. I am particularly indebted to J. Nicholls for assistance in evaluating the work on the surface phenomena.

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TABLE 1

Some Physical Properties of Mars and Earth

	Mars	Earth
Mass (g)	0.646×10^{27}	5.98×10^{27}
Diameter (km)	6800	12,800
Average density ($g\ cm^{-3}$)	3.96	5.52
Surface gravitational acceleration ($cm\ sec^{-2}$)	370	981
Mean distance from Sun (km)	228×10^{6}	150×10^{6}
Angle between rotation axis and orbital plane (deg.)	24.5	23.5
Length of year (days)	687	365
Length of southern spring (days)	146	91
Length of southern summer (days)	160	87
Length of southern fall (days)	199	93
Length of southern winter (days)	182	94
Length of day (hours)	24.6	24

TABLE 2

"Old" Determinations of the Surface Pressure

No.	Year	Authors	Method	Pressure (mb)	Remarks
1	1926	Menzel	Vis. and Pg. Albedo	---	Rejected
2	1929	Lyot	Vis. polarimetry	---	Rejected
3	1934	Barabascheff	Pg. photometry	50	Doubtful
4	1940	Barabascheff	" "	116	Doubtful
5	1941	Scharonow	" "	120	Indirect
6	1944	Sytinskaya	" "	112	Doubtful
7	1944	Fessenkoff	" "	125	Illusory
8	1945	Vaucouleurs	Vis. photometry	93	Approx.
9	1948	Hess	Theoret. Meteo.	80	Illusory
10	1948	Dollfus	Vis. polarimetry	80	Prelim.
11	1951	Dollfus	Vis. photometry	95	Approx.
12	1951	Dollfus	Vis. polarimetry	83	Final

TABLE 3

Computer Periapses for a Martian Orbiter

Apoapsis	Periapses at Designated Lifetimes				
	50 yrs.	10 yrs.	5 yrs.	1 yr.	0.5
	"Conservative" Atmosphere				
Circular	5500 km	3100	2400	1600	1400
5,000 km		2000	1450	850	700
10,000	3100	1400	1100	700	600
20,000	2100	1100	900	625	550
30,000	1800	1000	800	600	500
50,000	1500	900	750	550	450
	"Realistic" Atmosphere				
Circular	1400	1000	900	650	560
5,000 km	690	430	350	240	210
10,000	550	350	290	210	190
20,000	460	300	250	190	180
30,000	420	280	230	180	170
50,000	380	240	210	170	160

TABLE 4

Recent Spectroscopic Determinations of Martian Surface Pressure

Author	Original Estimate (mb)	Revised Estimate (mb)	Remarks
1. KMS	25 ± 15	33 ± 30	Revision based on Martian CO_2 abundance of 45 ± 25 m-atm.
2. OK	17 ± 3 (p. e.)	37 (upper limit)	" " " " "
3. Moroz	15^{+10}_{-5}	13^{+25}_{-8}	Revision based on Martian CO_2 abundance of 45 ± 25 m-atm.
4. Hanst and Swan	56 ± 31	--	Based on Martian CO_2 abundance of 28 ± 13 m-atm.

KMS -- Kaplan, L. D., Münch, G., and Spinrad, H., Ap. J. 139, 1 (1964).

OK -- Owen, T. C., and Kuiper, G. P., Comm. Lunar and Planet. Lab., 2, 113(1964).

Moroz -- Moroz, V., Astron. Zhur. 41, 350 (1964).

Hanst and Swan -- Hanst, P., and Swan, P., Avco Report (1965).

TABLE 5

Current Literature Estimates of the Surface Pressure

Author	Technique	Pressure (mb)
Kaplan, Münch, Spinrad (revised by Cann et al)	Near Infrared Spectroscopy	33 ± 30
Owen and Kuiper (revised by Cann et al)	Near Infrared Spectroscopy	37 (upper limit)
Moroz (revised by Cann et al)	Near Infrared Spectroscopy	13^{+25}_{-8}
Hanst and Swan	Near Infrared Spectroscopy	56 ± 31
Musman	Ultraviolet (3300A) Albedo	19 (pure CO_2) 27 (pure N_2)
Evans	Ultraviolet (2400-3500A) Spectrum	6 ± 3 (pure CO_2) 9 ± 4 (pure N_2) 13 ± 6 (pure A)

TABLE 6

Molecular Abundances in the Atmosphere

Molecule	Abundance
CO_2	45 ± 25 m atm.
H_2O	14 ± 7 μ precipitable H_2O (variable in time and space)
O_2	$<$ 2 cm atm.
O_3	$<$ 4 μ atm.
CH_3CHO	$<$ 60 μ atm.
CO	$<$ 1 cm atm.
CH_4	$<$ 1 mm atm.
NH_3	$<$ 1 mm atm.
NO_2	$<$ 10 μ atm.
N_2O	$<$ .8 mm atm.
NO	$<$ 20 cm atm.
H_2S	$<$ 7.5 cm atm.
H_2CO	$<$ 0.3 cm atm.
COS	$<$ 0.2 cm atm.

TABLE 7

Microwave Temperature Measurements of Kellermann

λ (cm)	T (°K)
6.0	192 ± 26
11.3	162 ± 18
21.3	190 ± 41

TABLE 8

Three Samples of Limonite Examined by Hovis

U.S.N.M. Specimen No.	Locality of Origin	Iron Oxide Minerals	Percent other Minerals	Other Minerals
109590	Cartersville, Georgia	Goethite	27	More than 90% quartz, minor mica group minerals
109592	Alabama	Goethite	5.3	Quartz
18274	Caracas, Venezuela	Goethite	47	More than 90% quartz

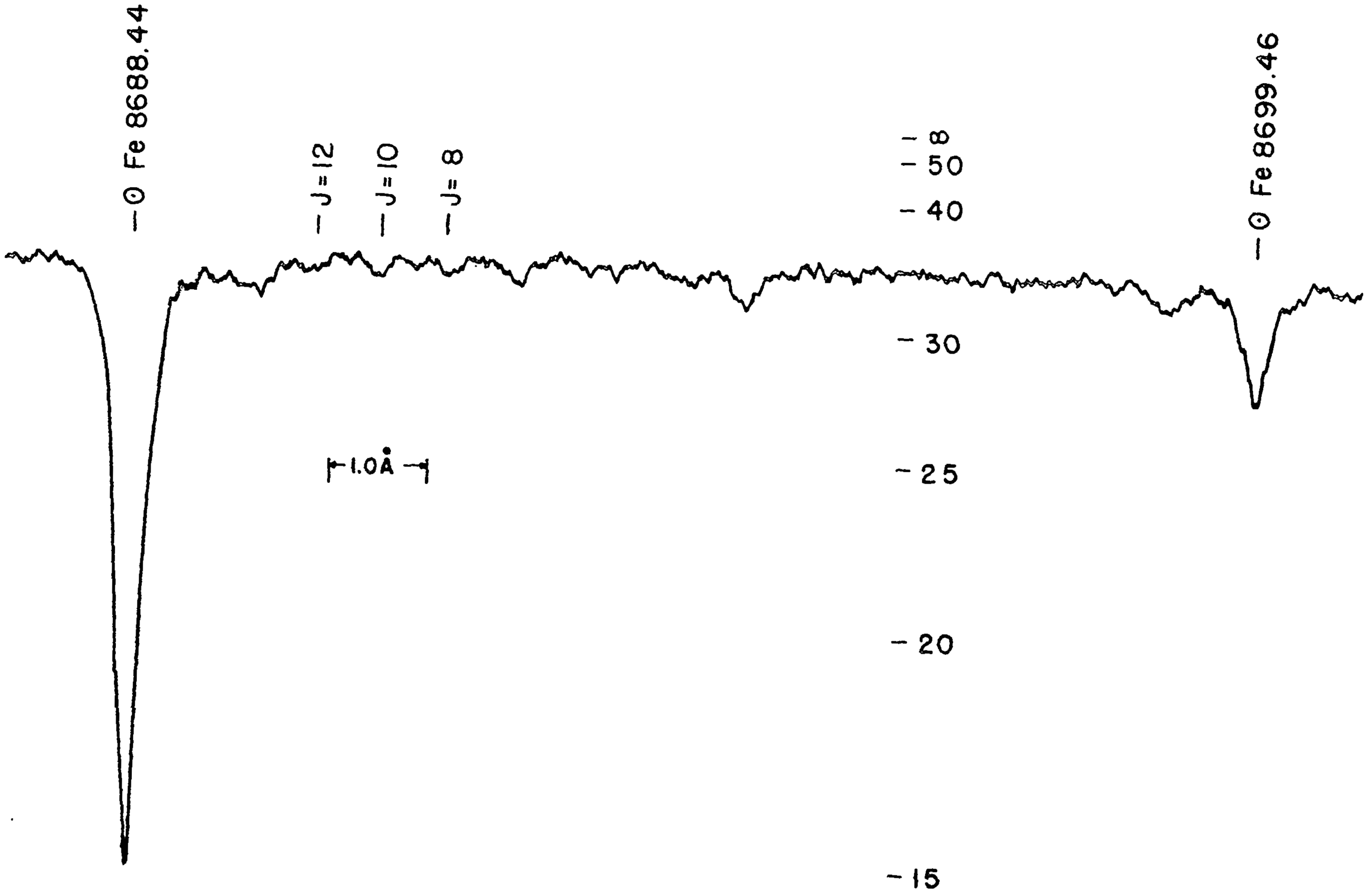


Fig. 1. A microphotometer tracing of the R-branch in the $5\nu_3$ CO_2 band of Mars. The measured lines J = 8, 10, 12, and two solar lines are shown[10].

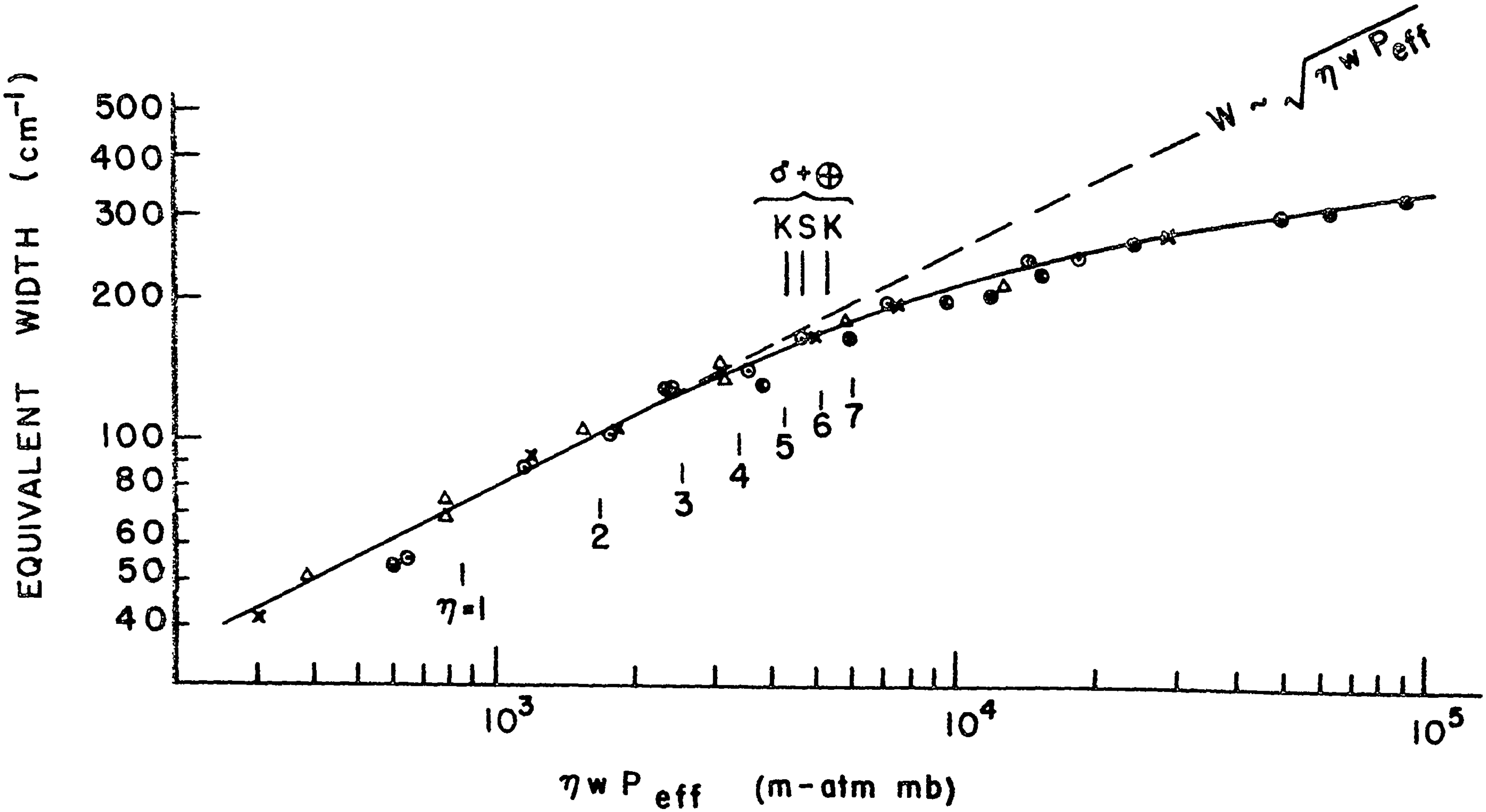


Fig. 2. Equivalent width of 2 μ band complex vs. CO_2 amount times effective pressure. The abscissa markings below the curve are for various telluric air-masses, η, above the curve for Earth plus Mars from Sinton (S) and Kuiper (K), upper and lower limits[10].

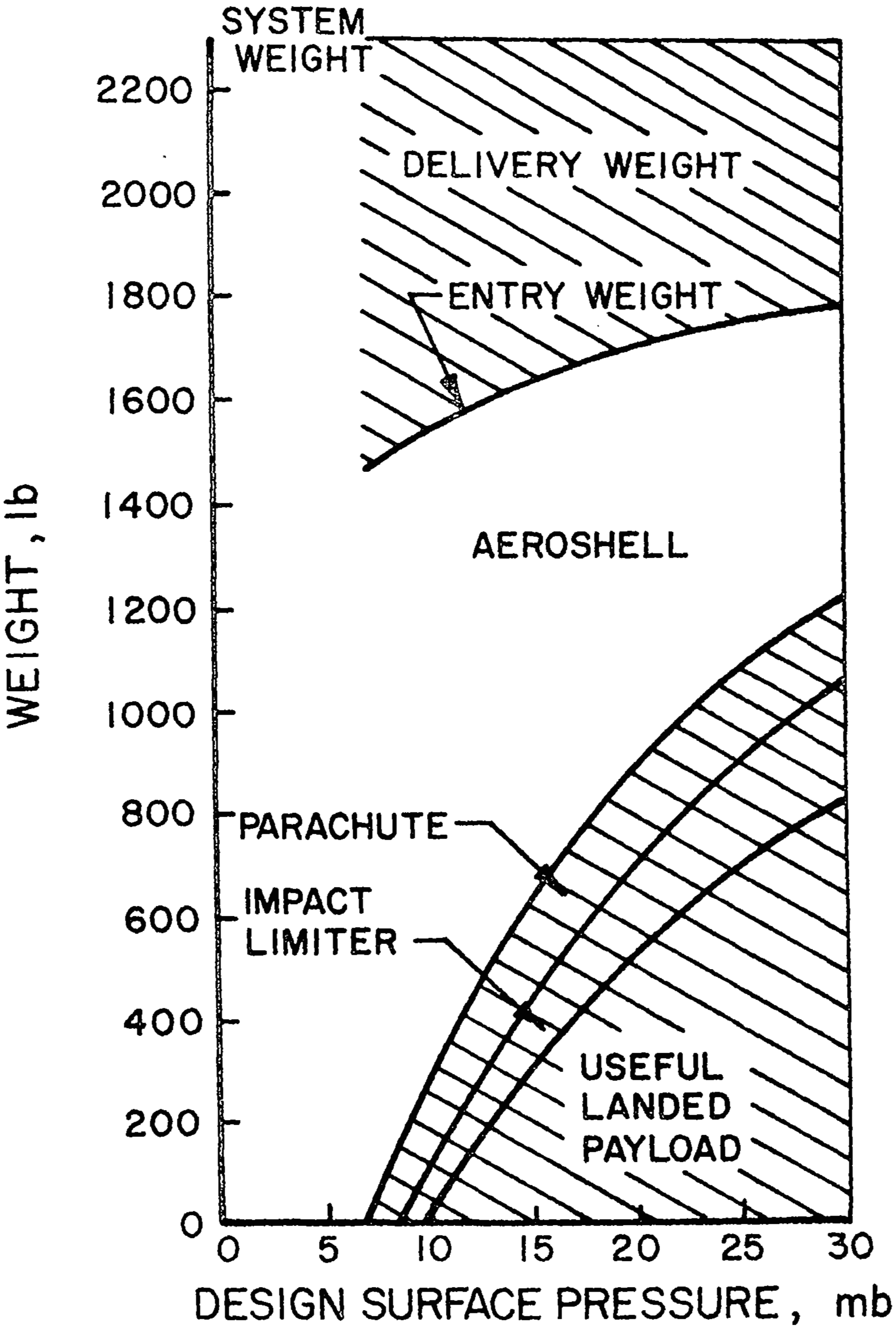


Fig. 3. The effect of atmospheric pressure on a particular capsule design[11].

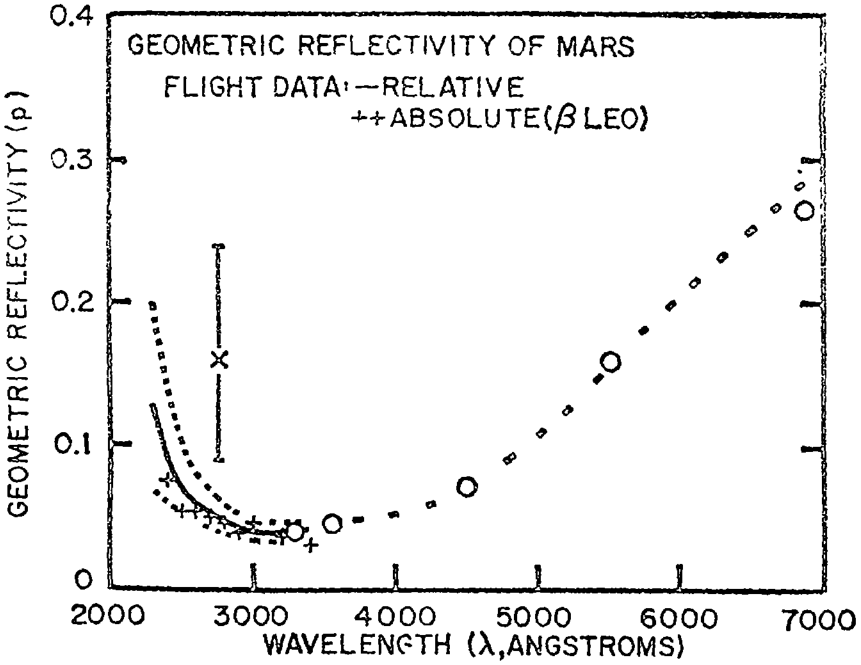
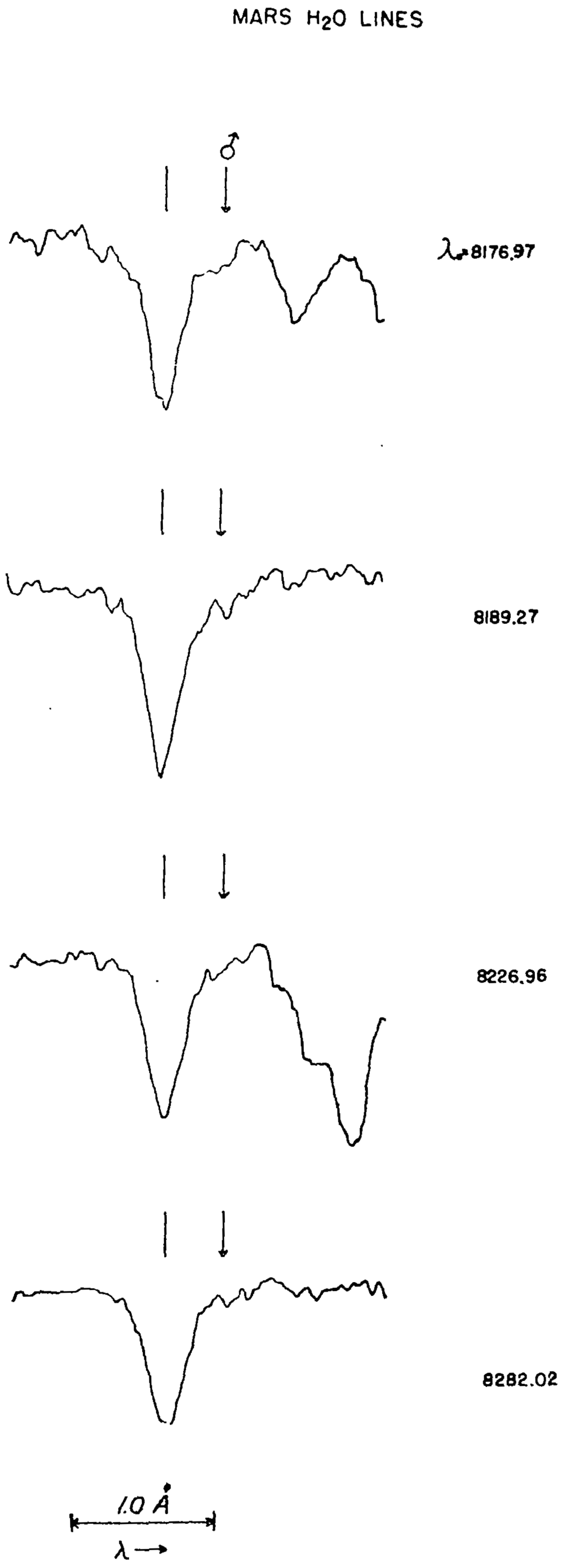
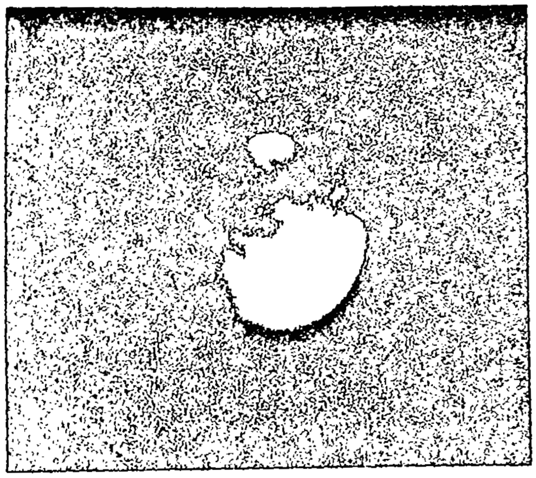


Fig. 4. The geometric reflectivity of Mars. Solid line, relative data adjusted to 0.04 at 3400 A; +, absolute reflectivity determined by comparison with β Leo, plotted independently. The dashed lines below 3400 A represent the error range applied to the relative data[15].

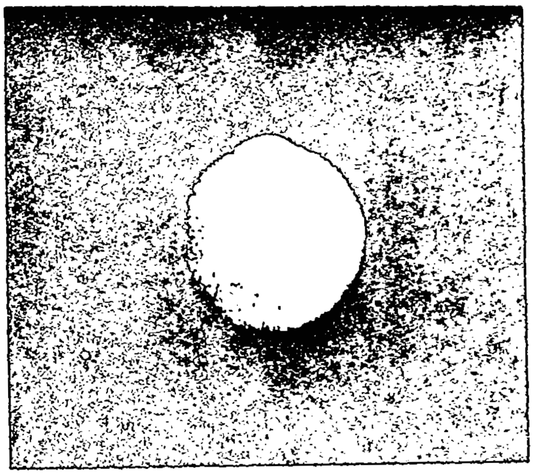


MARS H_2O LINES

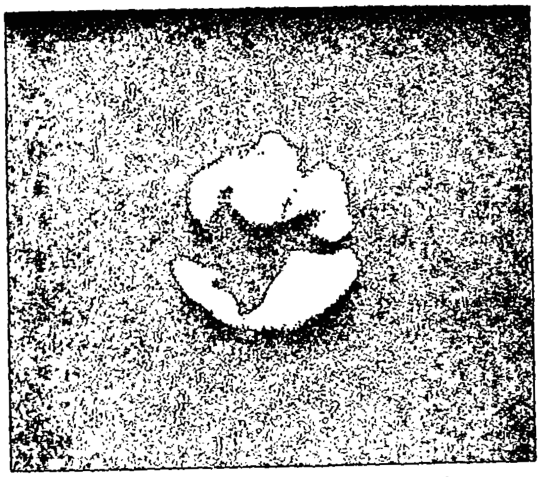
Fig. 5. Doppler shifted Martian H_2O lines[16].



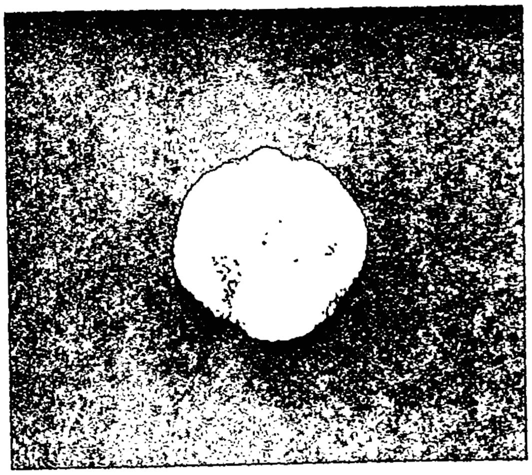
1. 1956 Aug 24 λ84°
U.T. 23:49 R
May 30 M.D.



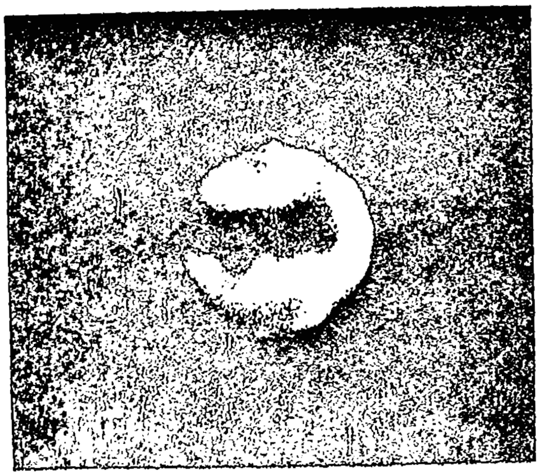
2. 1956 Aug 24 λ79°
U.T. 23:27 B
May 30 M. D.



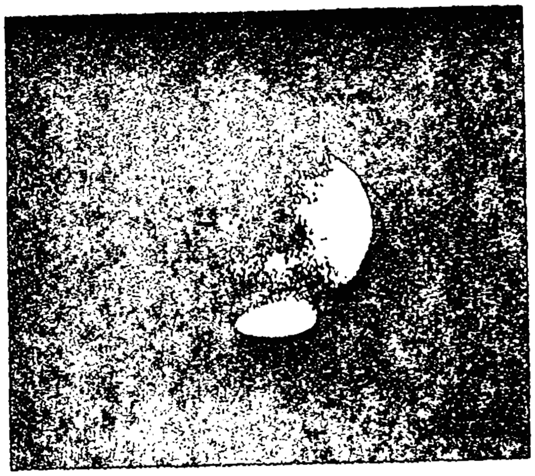
3. 1941 Oct 11 λ305°
U.T. 6:00 O
July 11 M.D.



4. 1941 Oct 11 λ320°
U.T. 7:07 B
July 11 M.D.

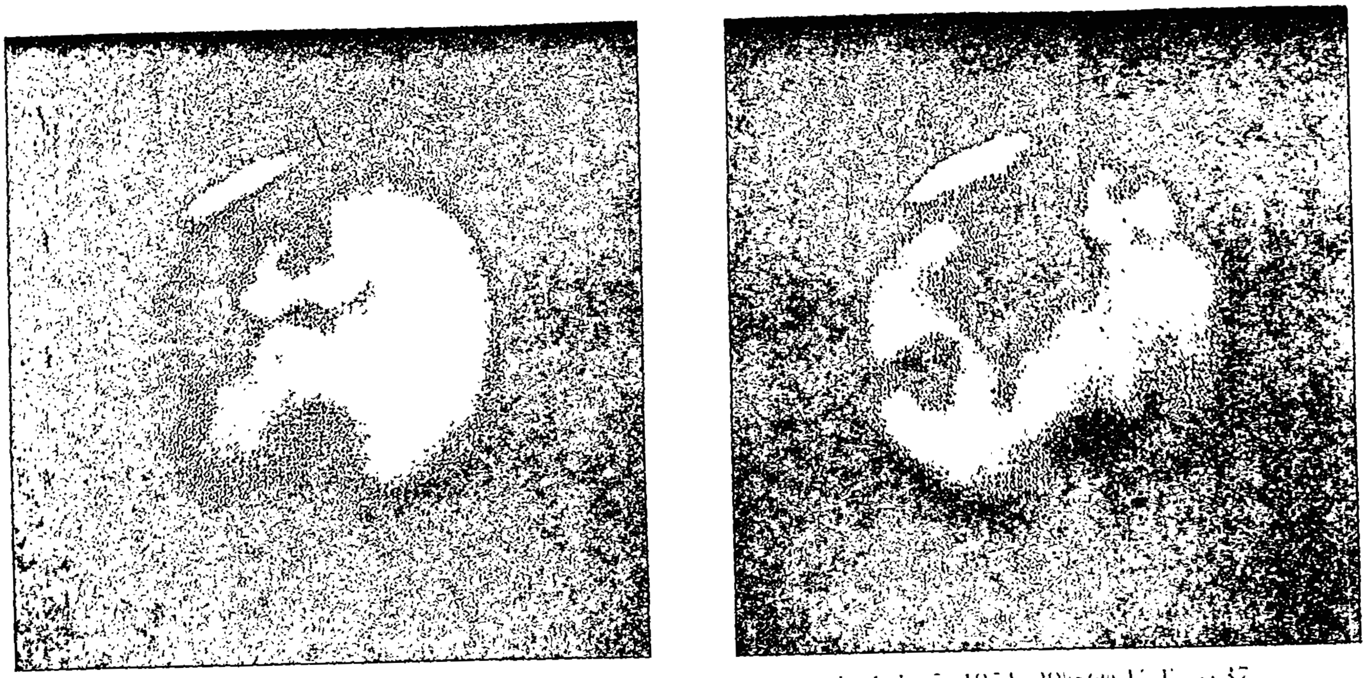


5 1926 Oct 27 λ10°
U.T. 6:48 Y
Aug 1 M.D.



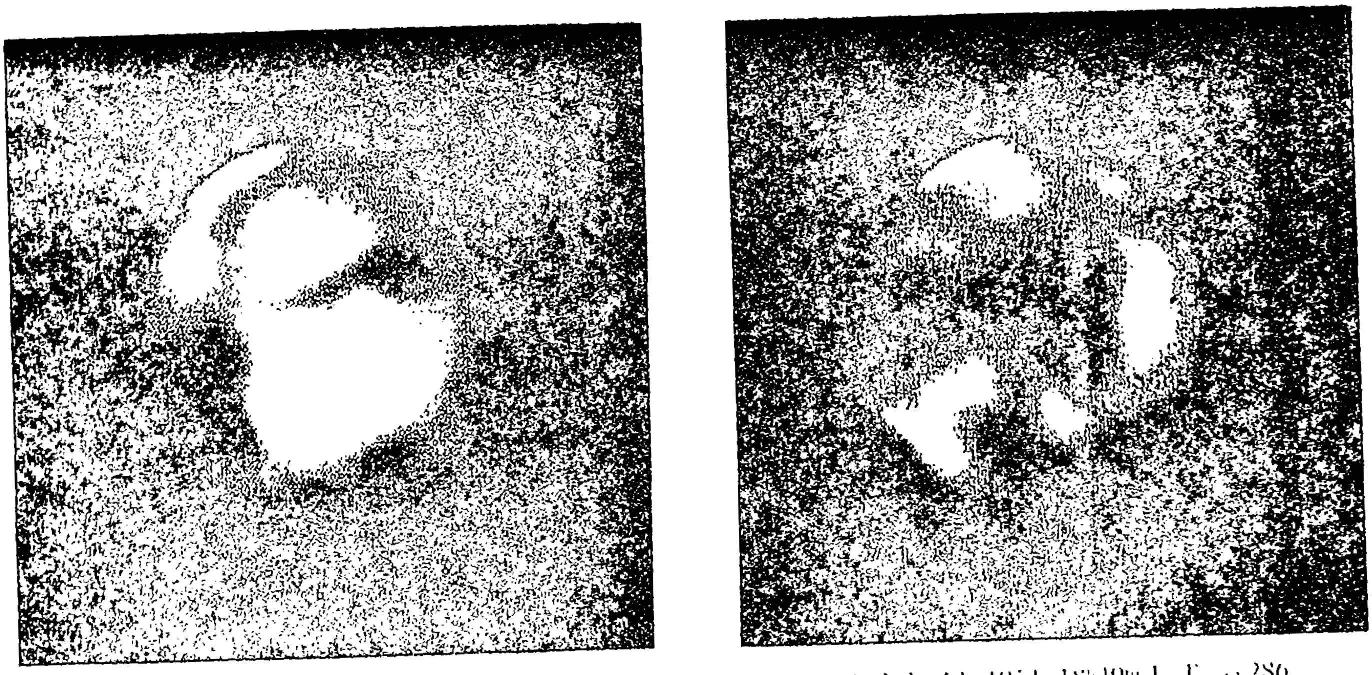
6. 1926 Oct 27 λ22°
U.T. 8:06 B
Aug 1 M.D.

Fig. 6. Comparisons of yellow and blue photographs showing the presence of the obscuring blue haze together with partial clearing[2].



(a) July 1, 1954, 21^h5^m U.T., ω 75°

(b) July 5, 1954, 20^h56^m U.T., ω 37



(c) July 11, 1954, 20^h16^m U.T., ω 331

(d) July 11, 1954, 18^h49^m U.T., ω 286

Fig. 7. The visual appearance of Mars in 1954[25].

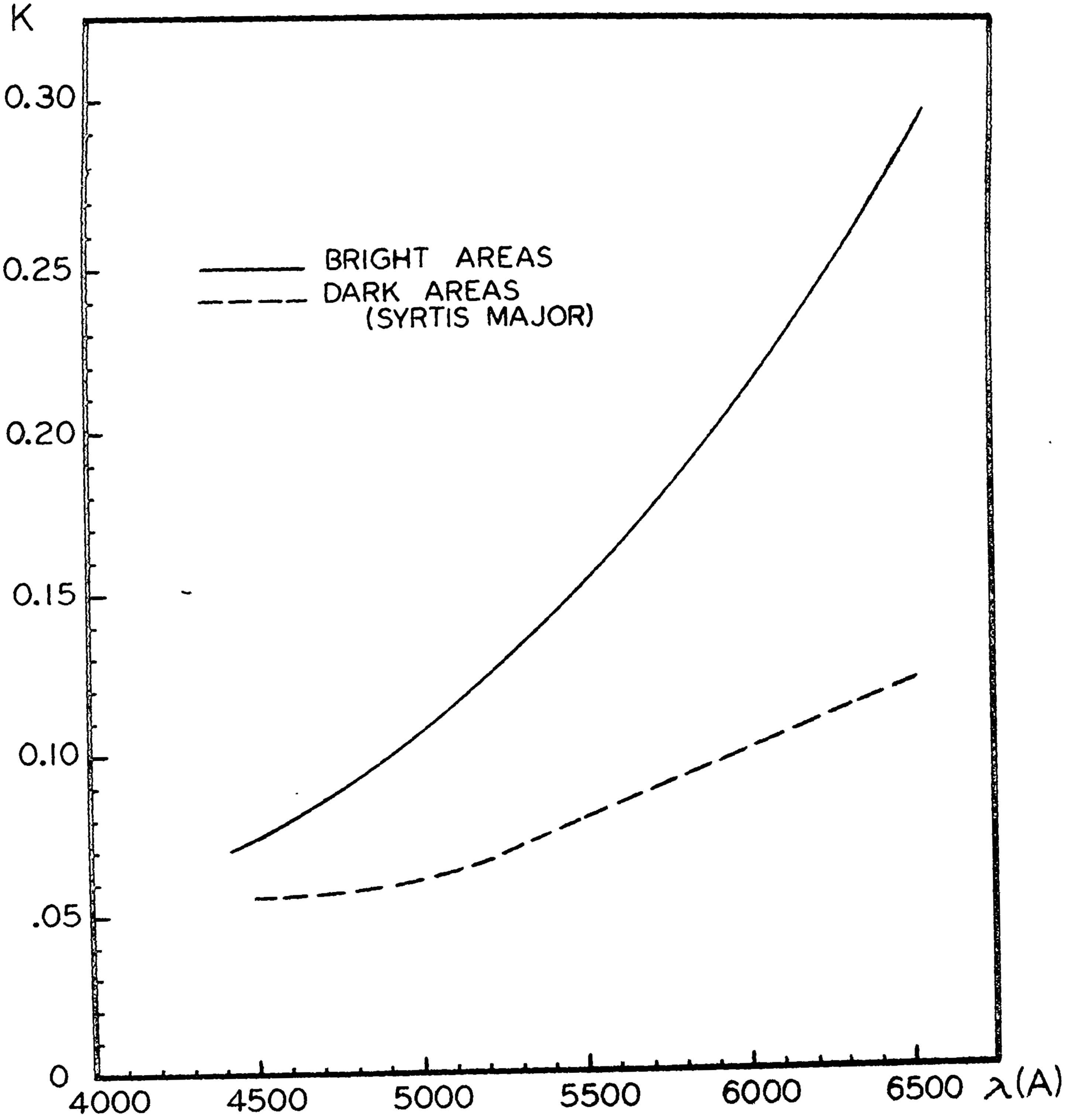


Fig. 8. The spectra of the bright and dark areas[26].

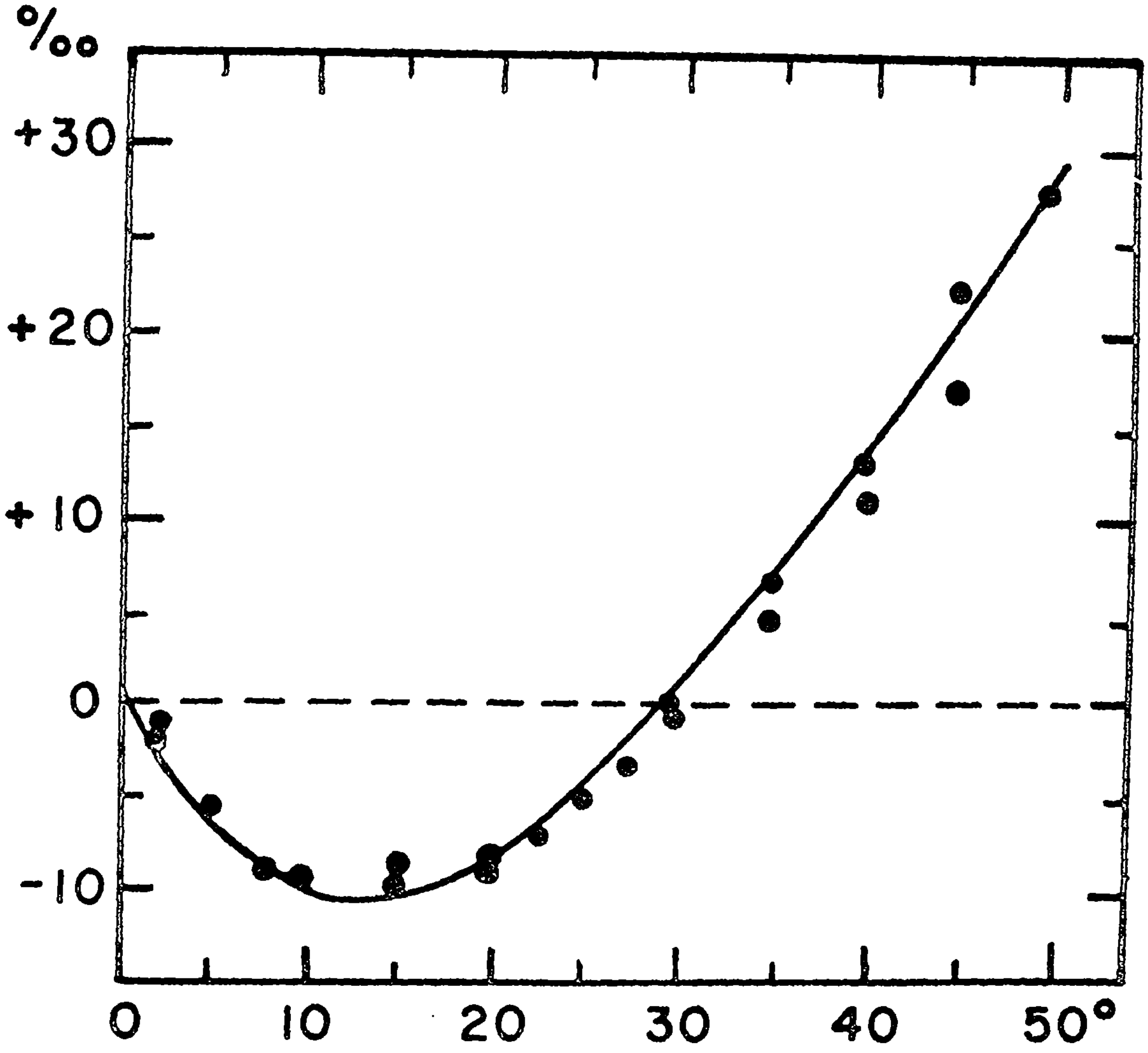
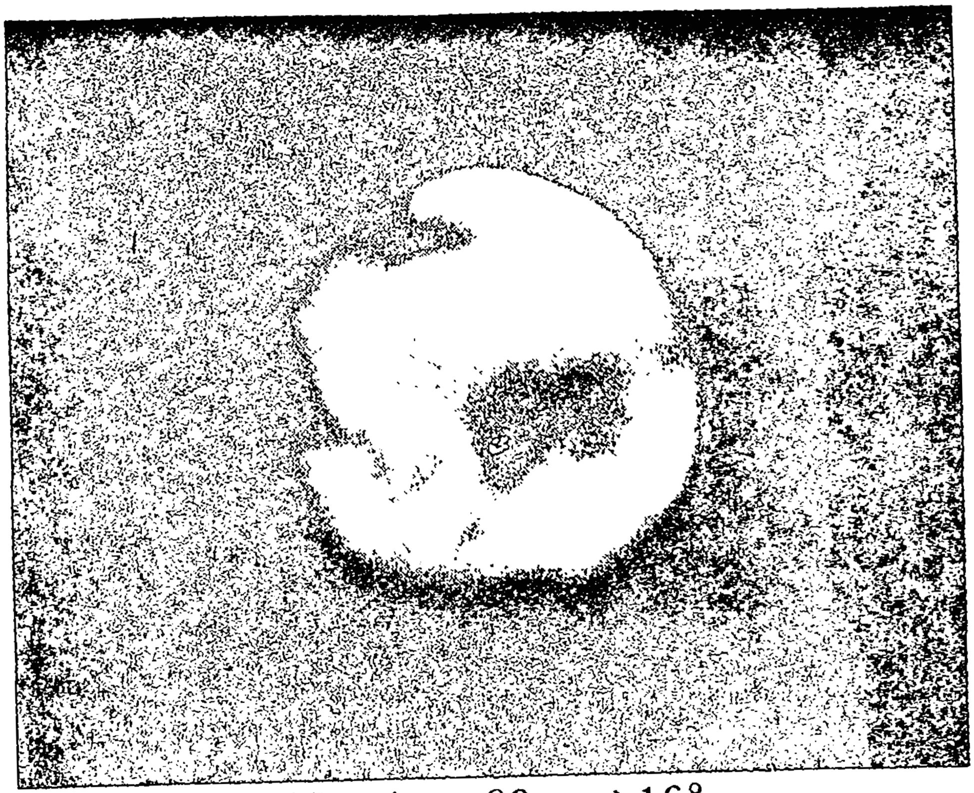
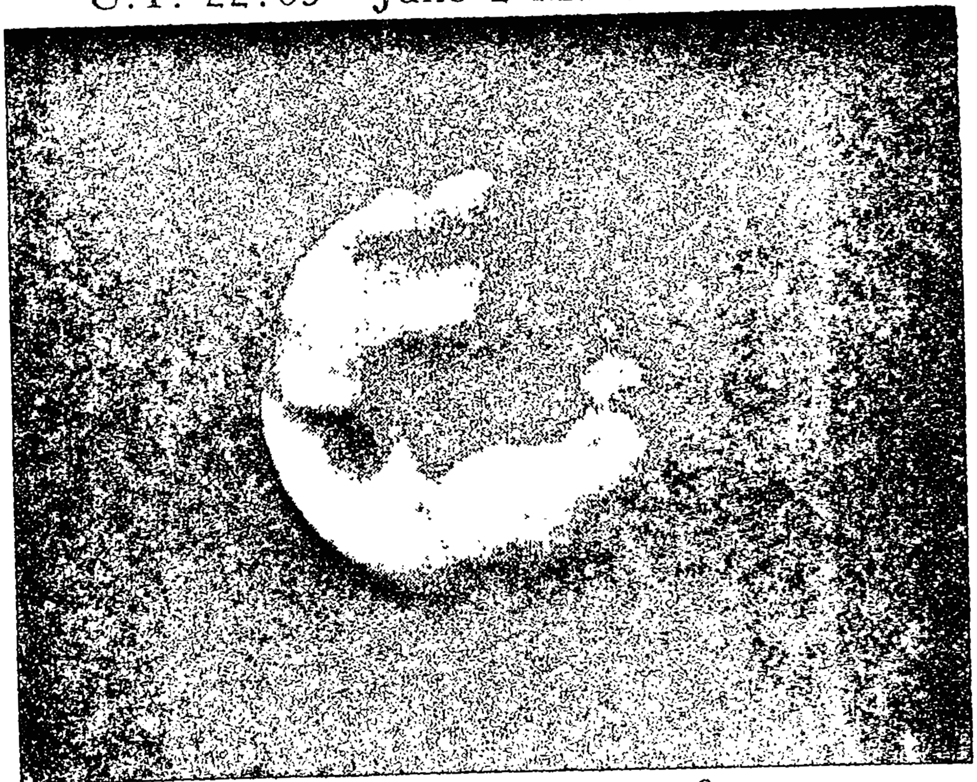


Fig. 9. The polarization of the bright areas vs. phase angle as reduced for a Rayleigh scattering molecular atmosphere with a pressure of 90 mb. The dots represent laboratory measurements of pulverized limonite[28].



2. 1956 Aug 29 λ16°
U.T. 22:09 June 2 M.D. R



5. 1941 Nov 10 λ38°
U.T. 6:09 July 30 M.D. R

Fig. 10. The great dust storm of 1956[2].

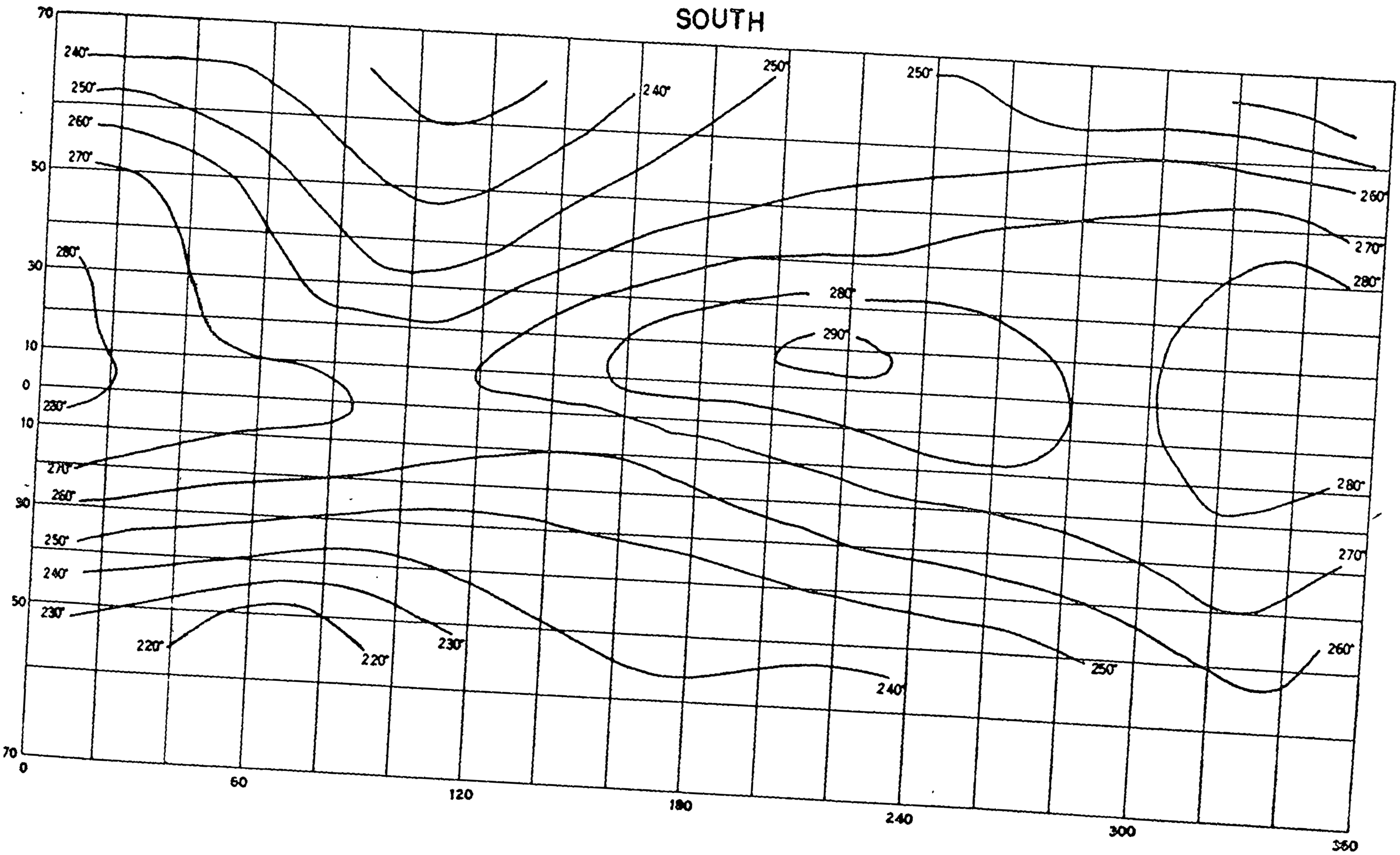


Fig. 11. Average Martian southern hemisphere summer isotherms[30].

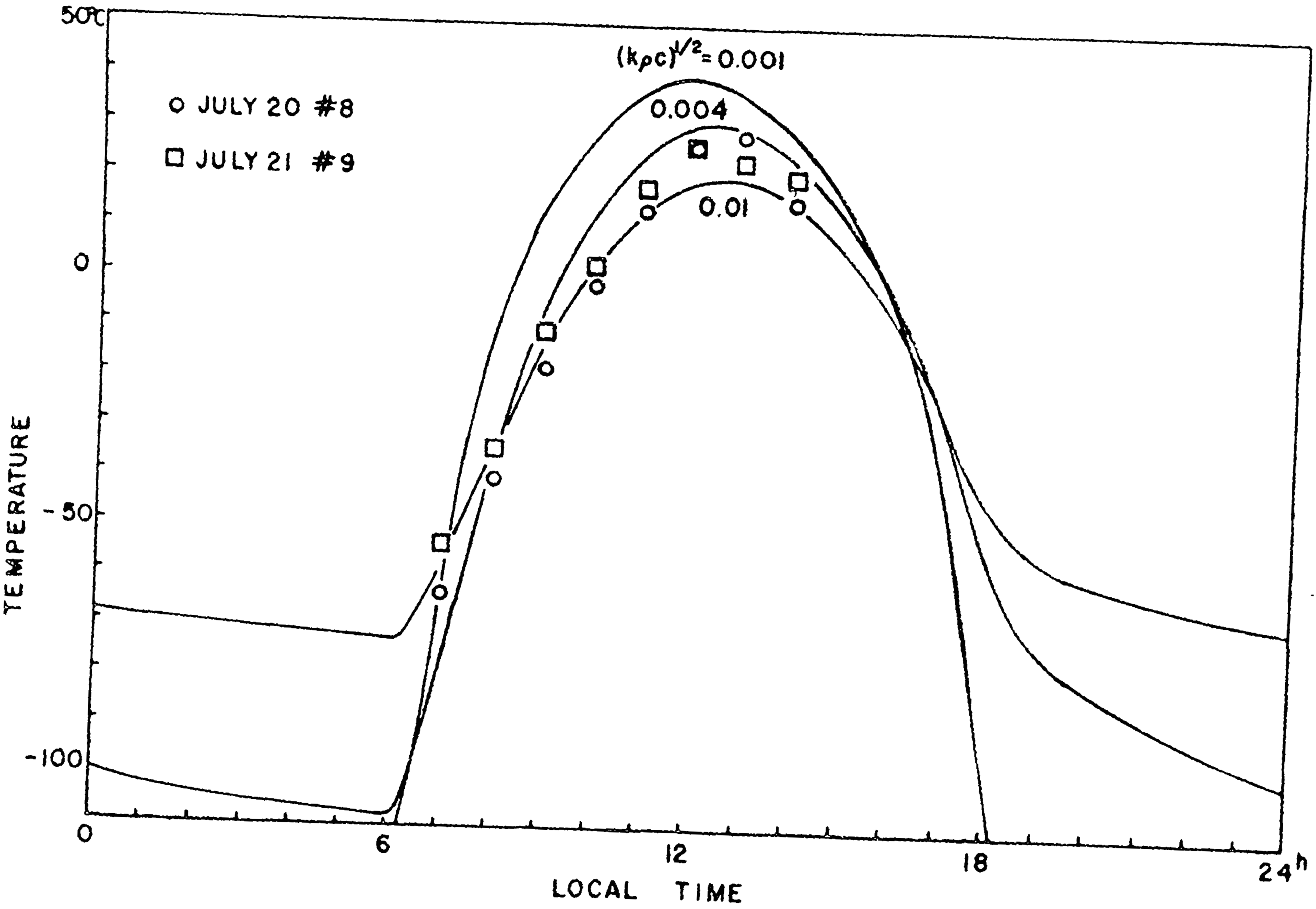


Fig. 12. Theoretical and observed diurnal temperature variation at the equator[32].

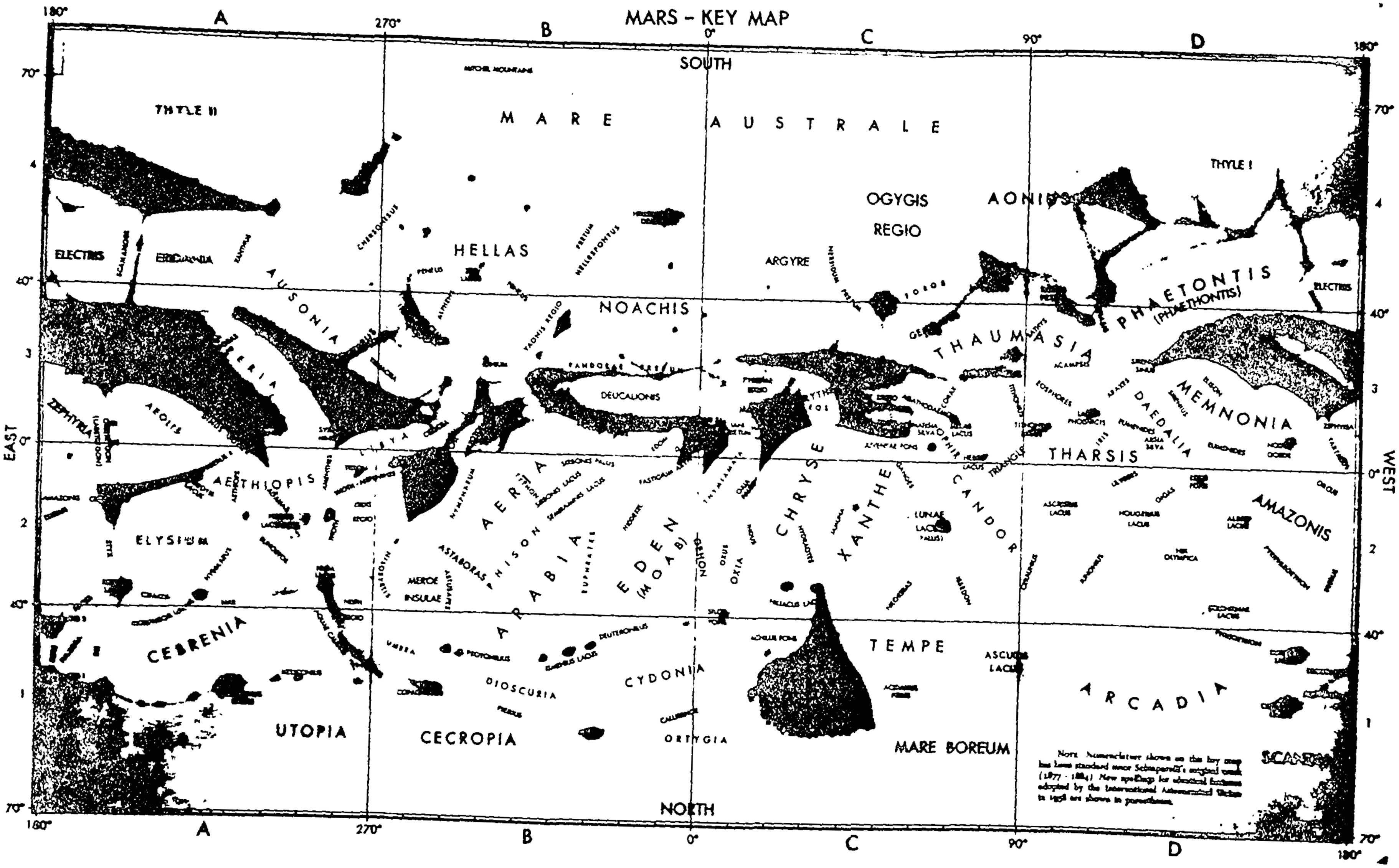


Fig. 13. A drawing of Mars by Slipher[2].

Fig. 14. A drawing of Mars in 1958 by Focas[33].

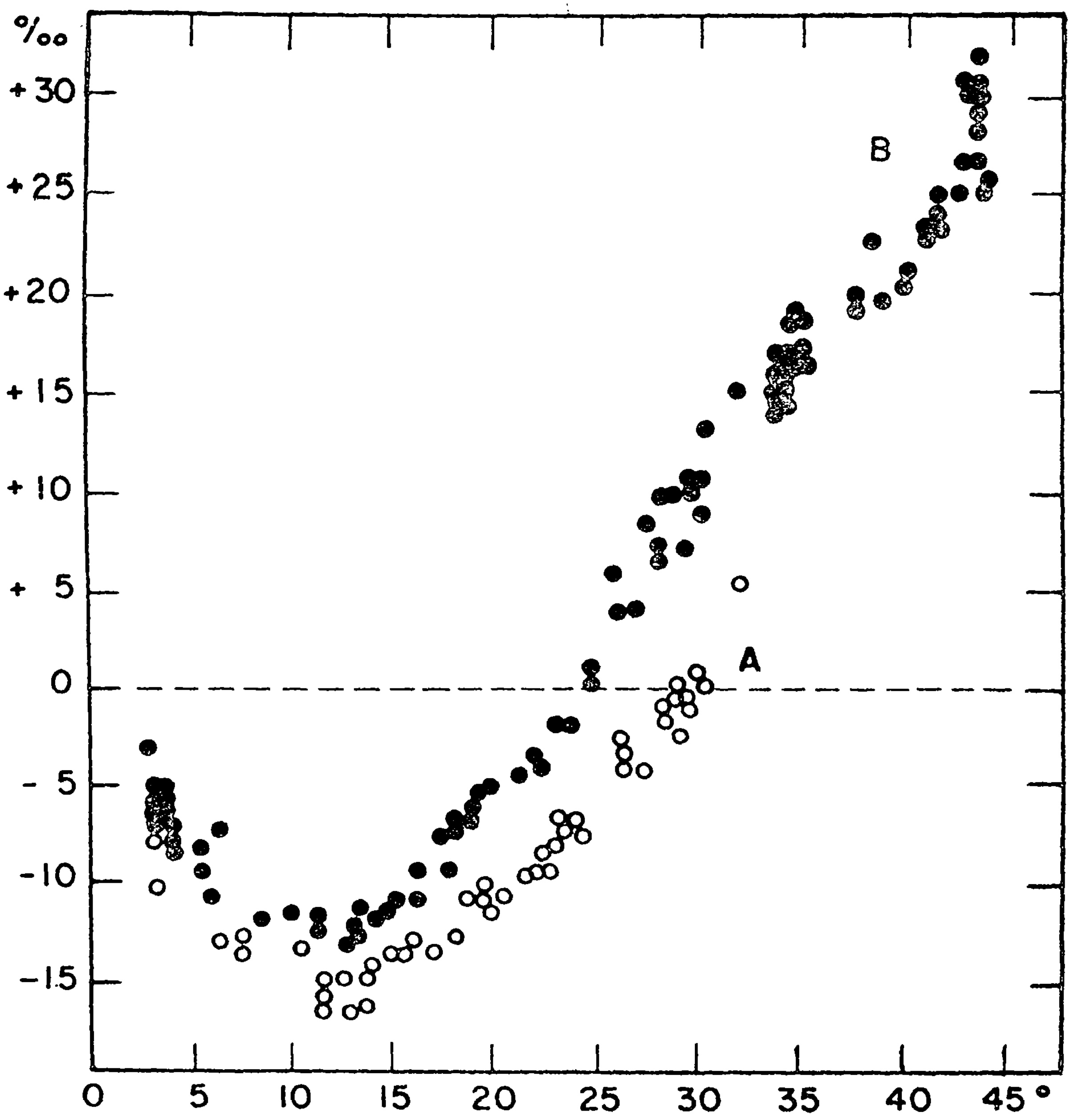


Fig. 15. The polarization vs. phase angle for the dark areas. The filled circles are for equatorial markings, the open circles for markings in the northern hemisphere at Martian spring[28].

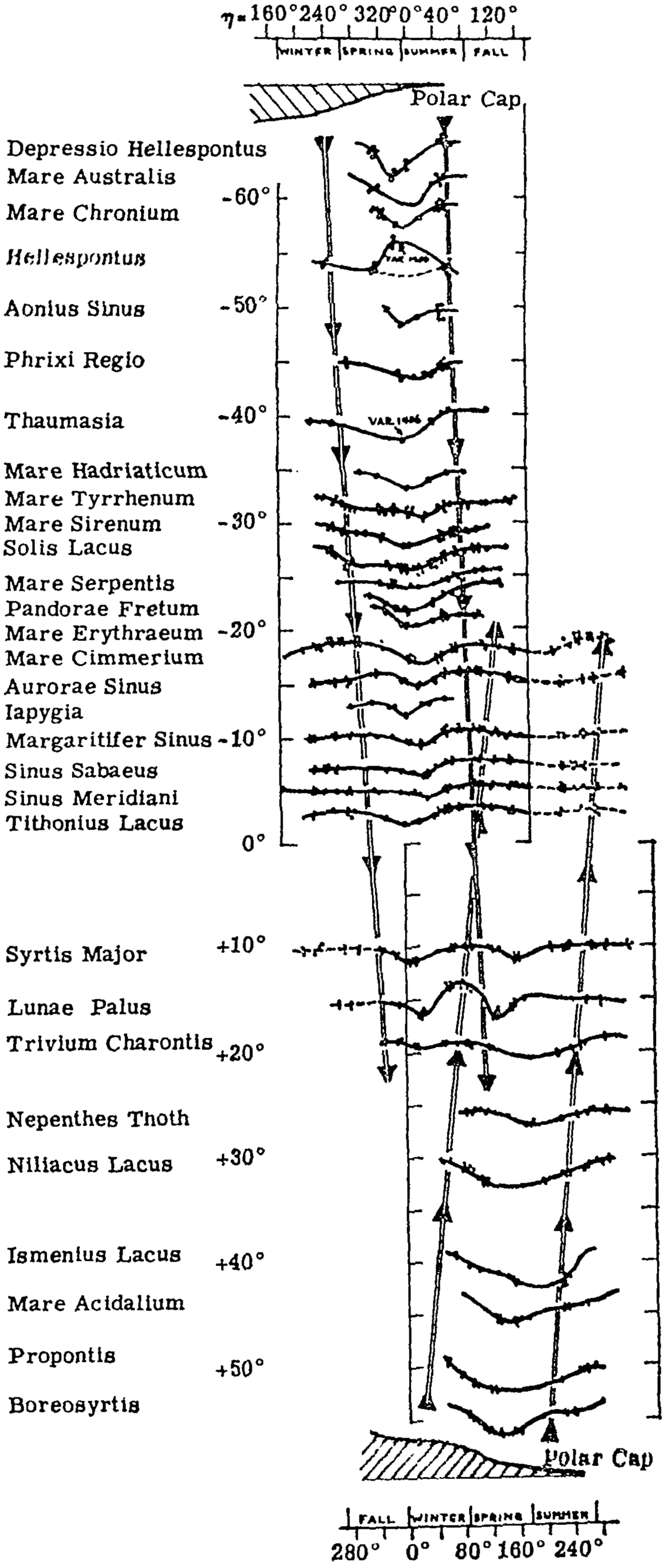
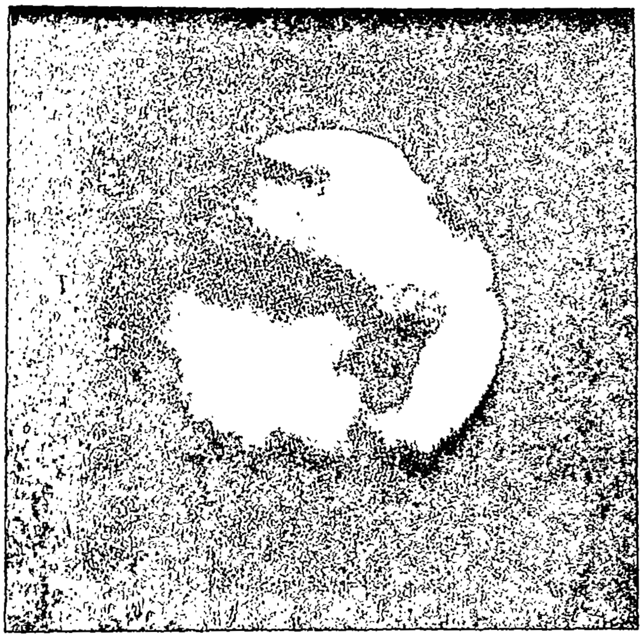


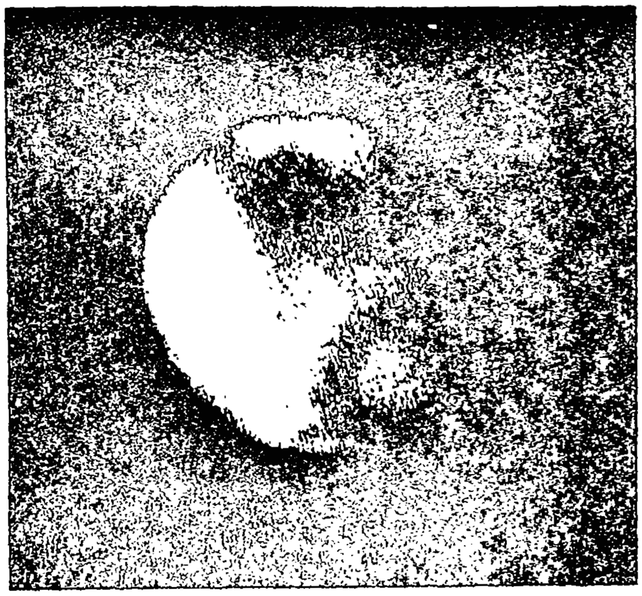
Fig. 16. Brightness of the dark areas vs. heliocentric longitude. South is at the top, north at the bottom[33].



2. 1907 July 3 λ270°
U.T. 4:21 Apr 7 M.D. Y

8. 1920 Apr 23 λ285°
U.T. 8:47 Jan 25 M.D. Y

9. 1922 June 18 λ260°
U.T. 7:25 Mar 16 M.D. Y



12. 1928 Dec 29 λ245°
Sept 28 M. D. Y

Fig. 17. Pronounced secular changes in the Thoth-Nepenthes region[2].

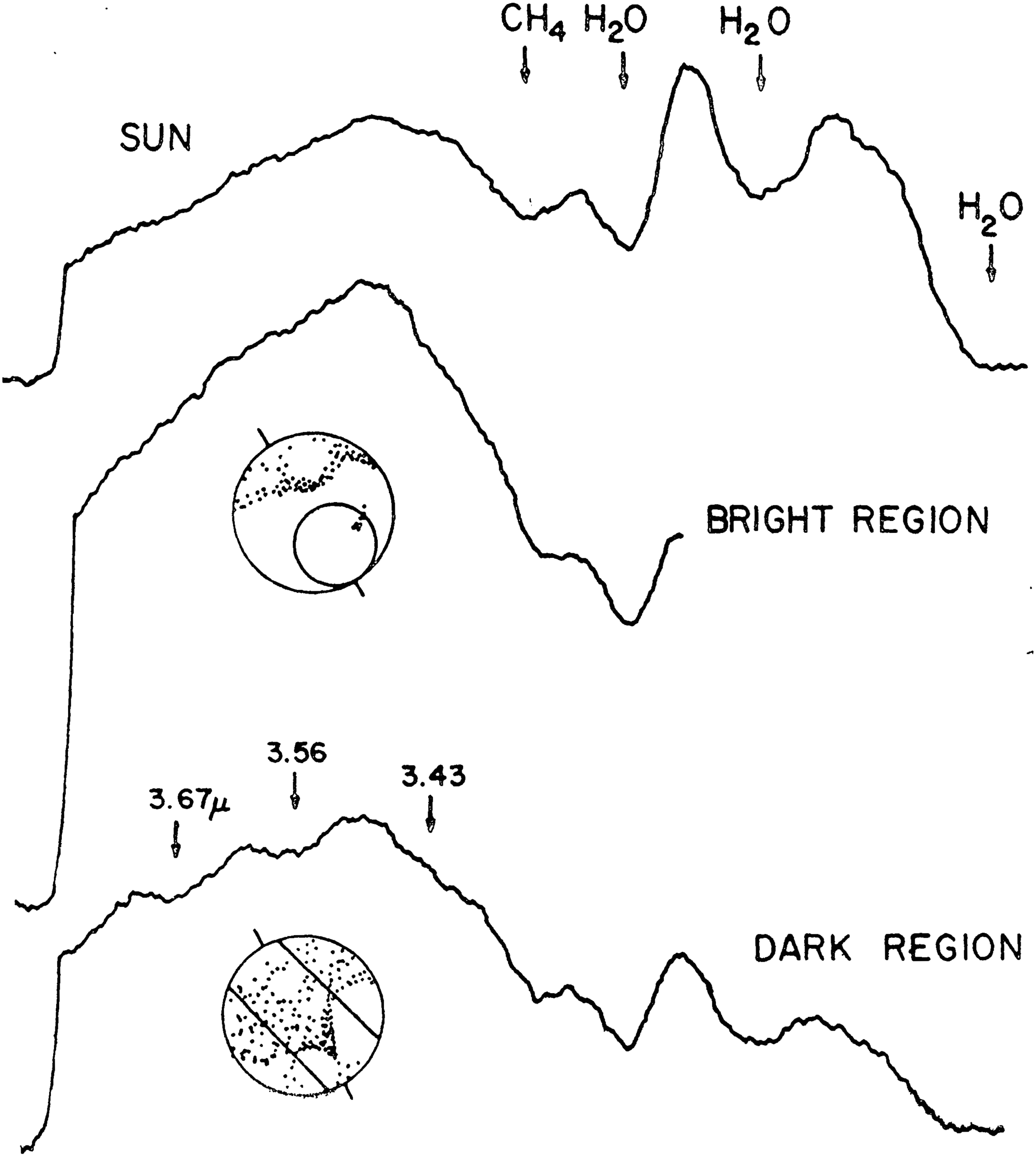


Fig. 18. Spectra of the Sun and Mars recorded at Mt. Palomar in October 1958[36].

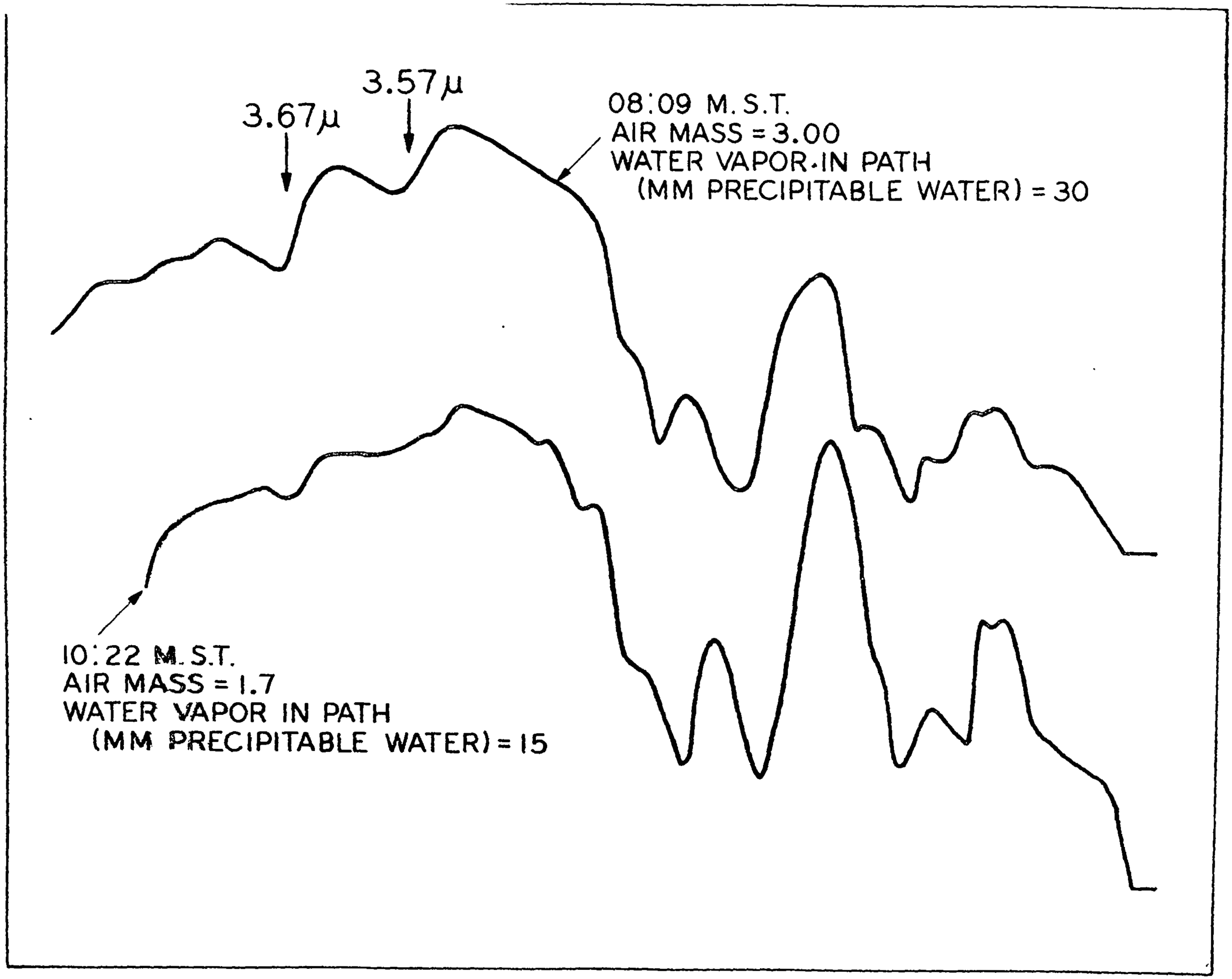


Fig. 19. Spectra of the Sun recorded at Denver on May 12, 1955[37].

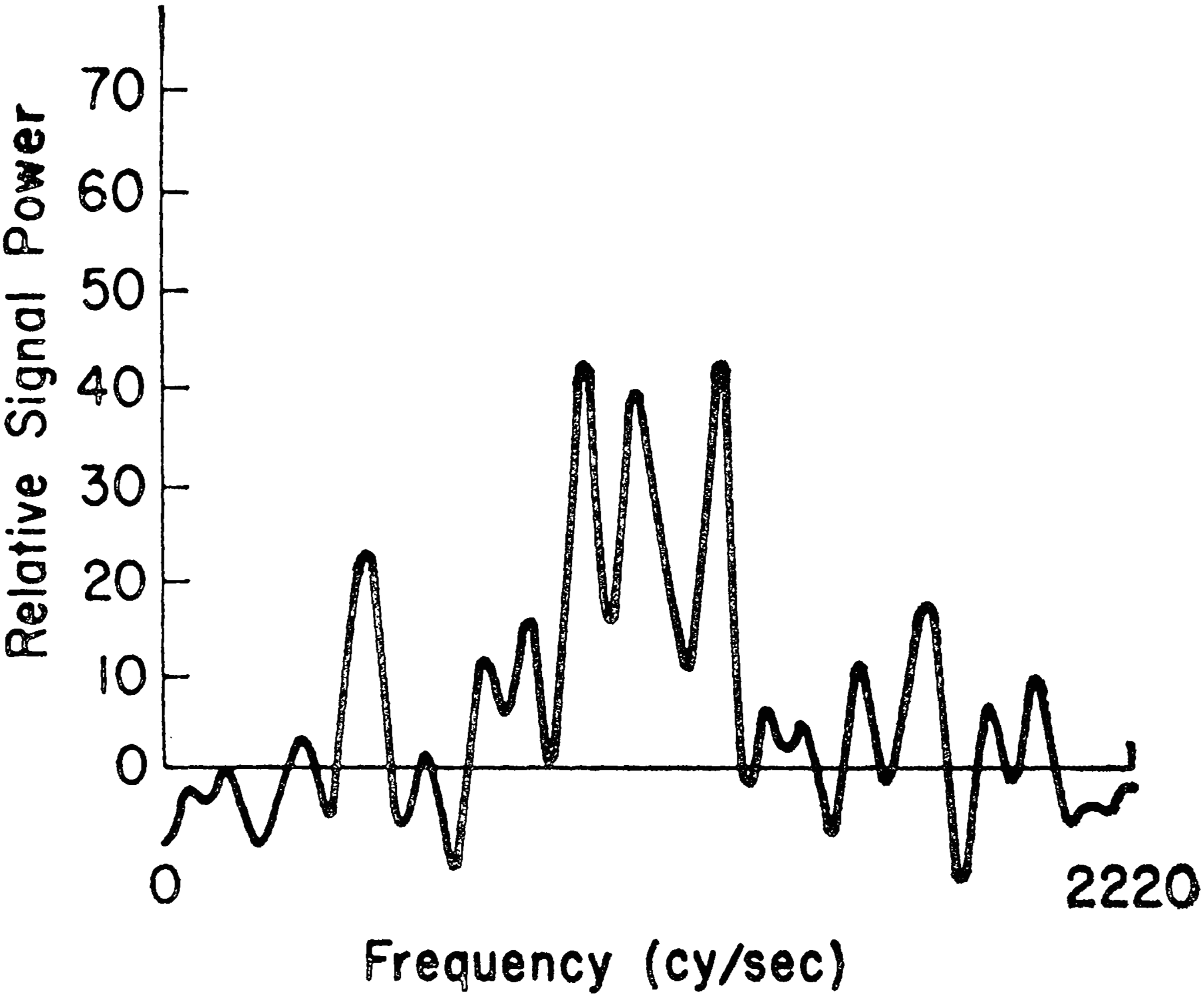


Fig. 20. A spectrogram showing the average 12.6 cm radar echo from Mars obtained over several weeks[40].

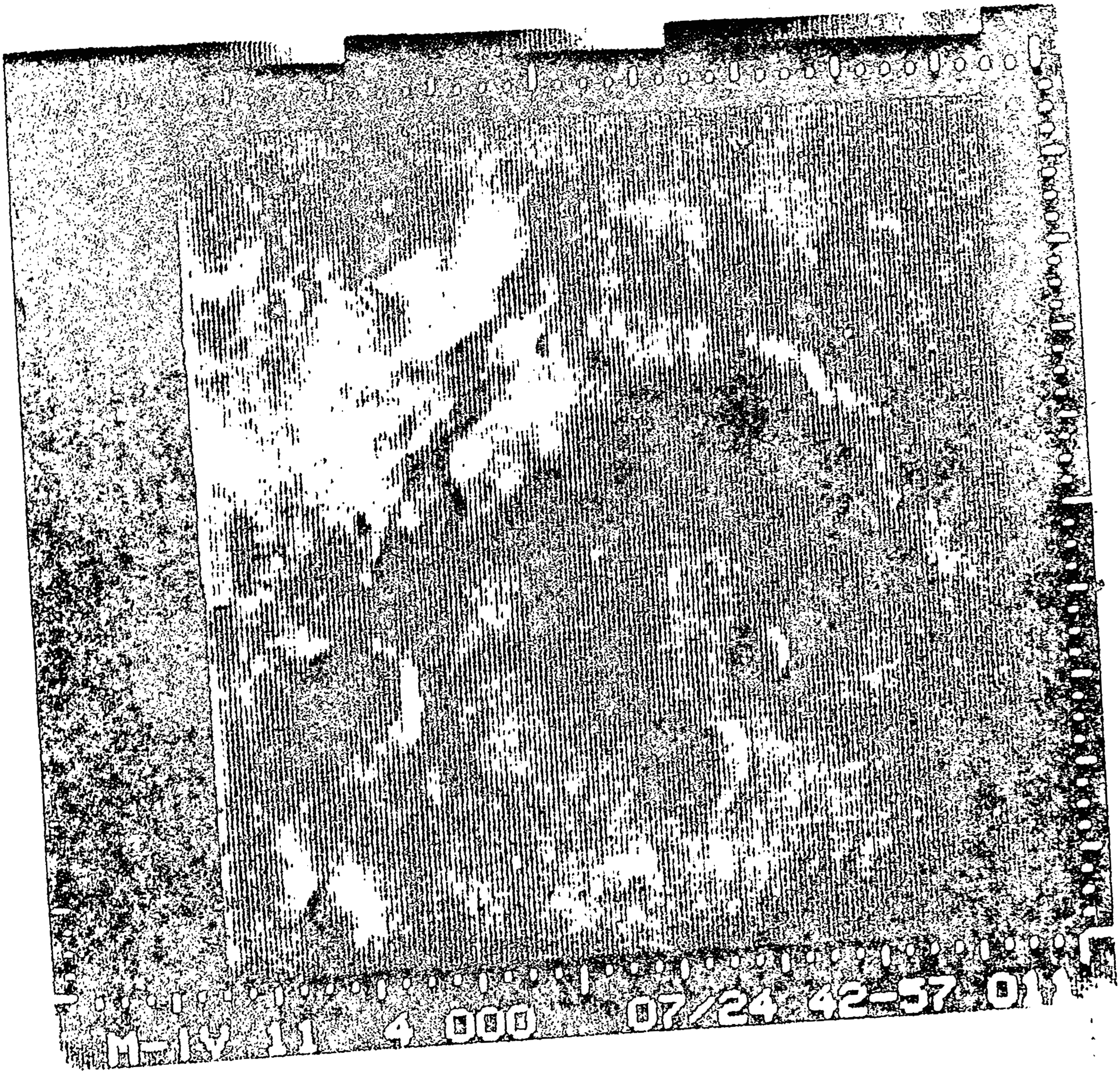


Fig. 21. Frame 11 of the Mariner IV T.V. series[43].

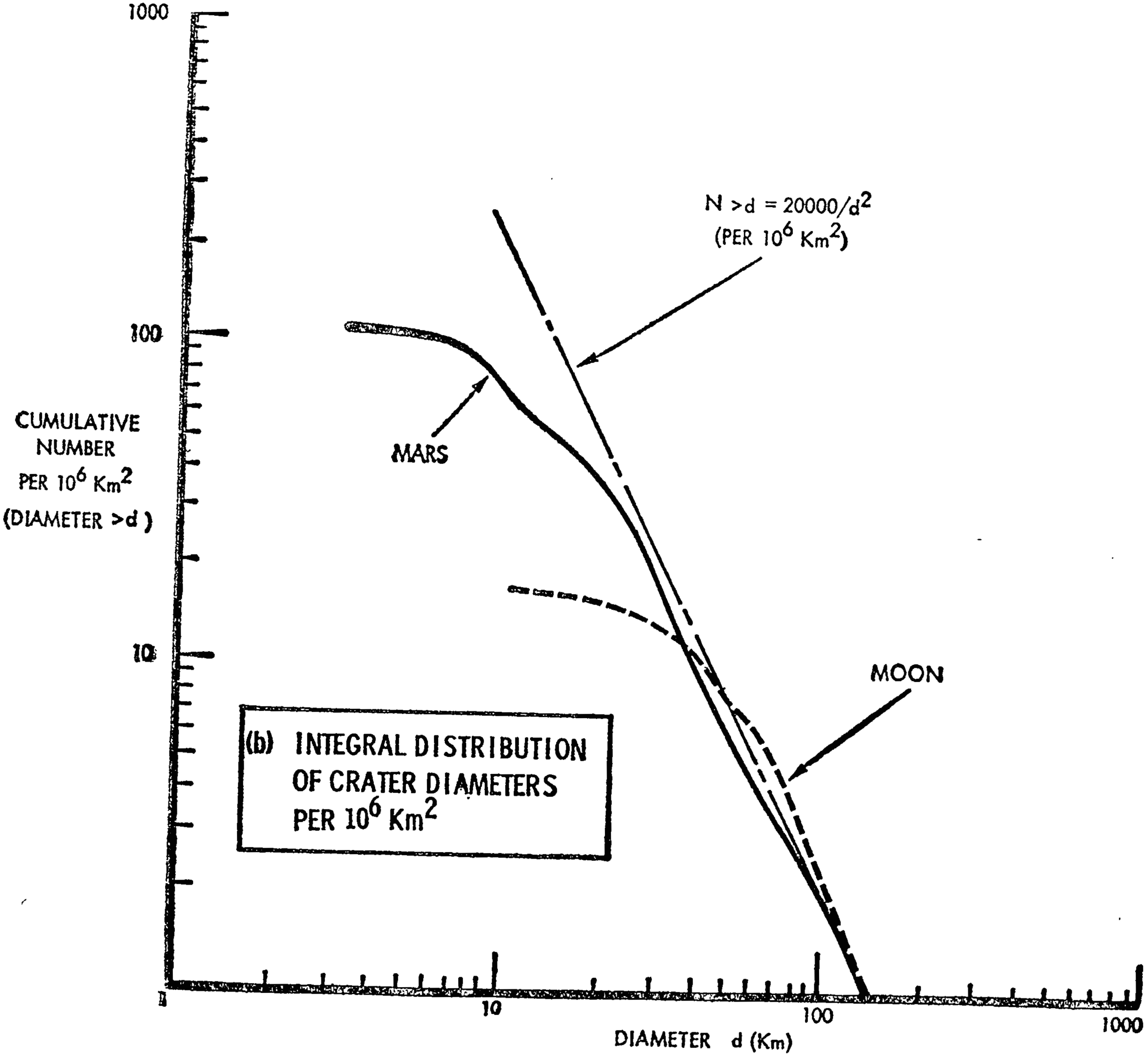


Fig. 22. A comparison of crater density vs. crater diamer for Mars and the Moon (averaged over maria and terrae)[43].

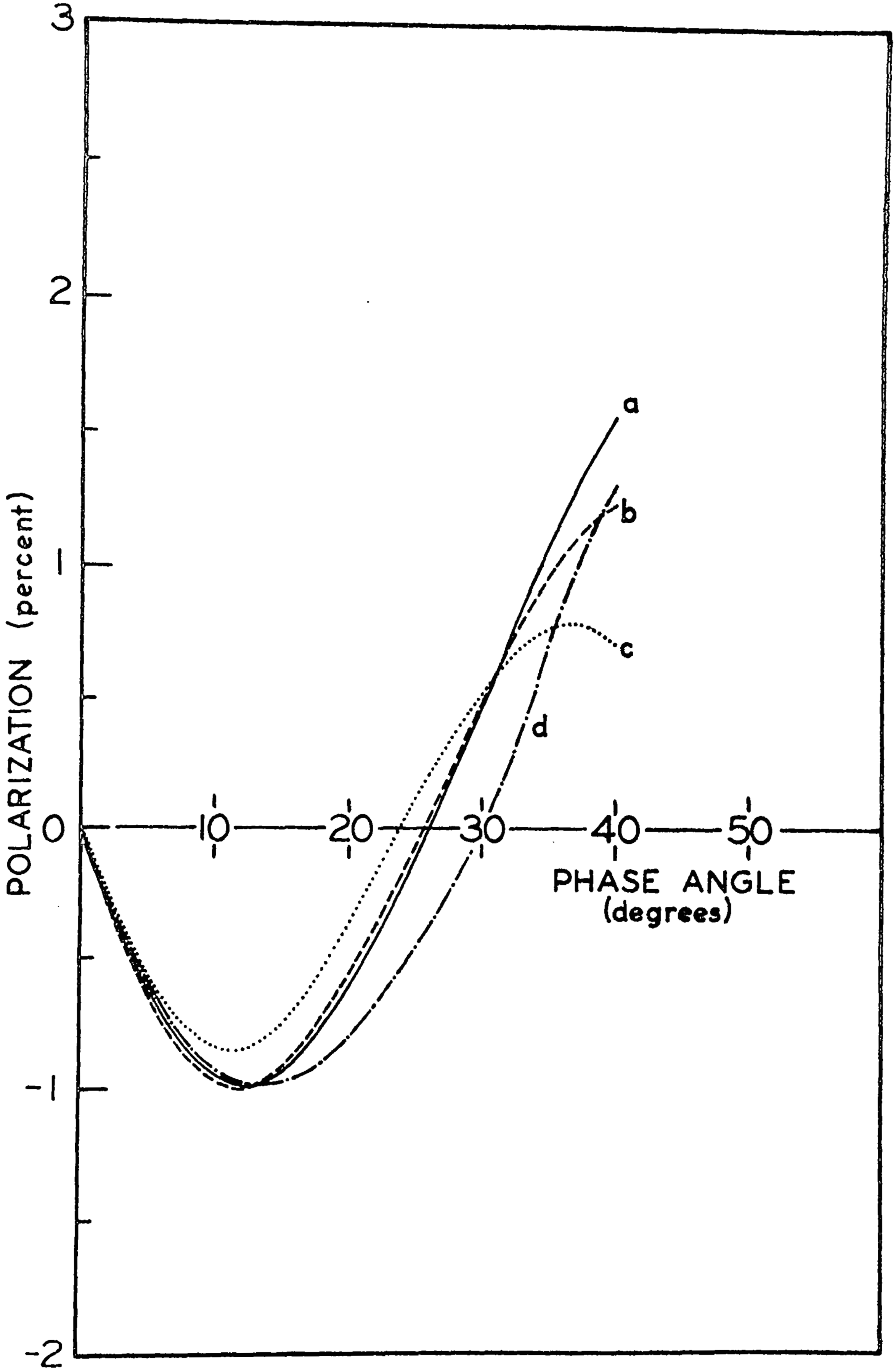


Fig. 23. The polarization vs. phase angle for the Martian bright areas. a - observed; b, c - derived for atmospheres containing aerosols of different distributions; d - pulverized limonite[46].

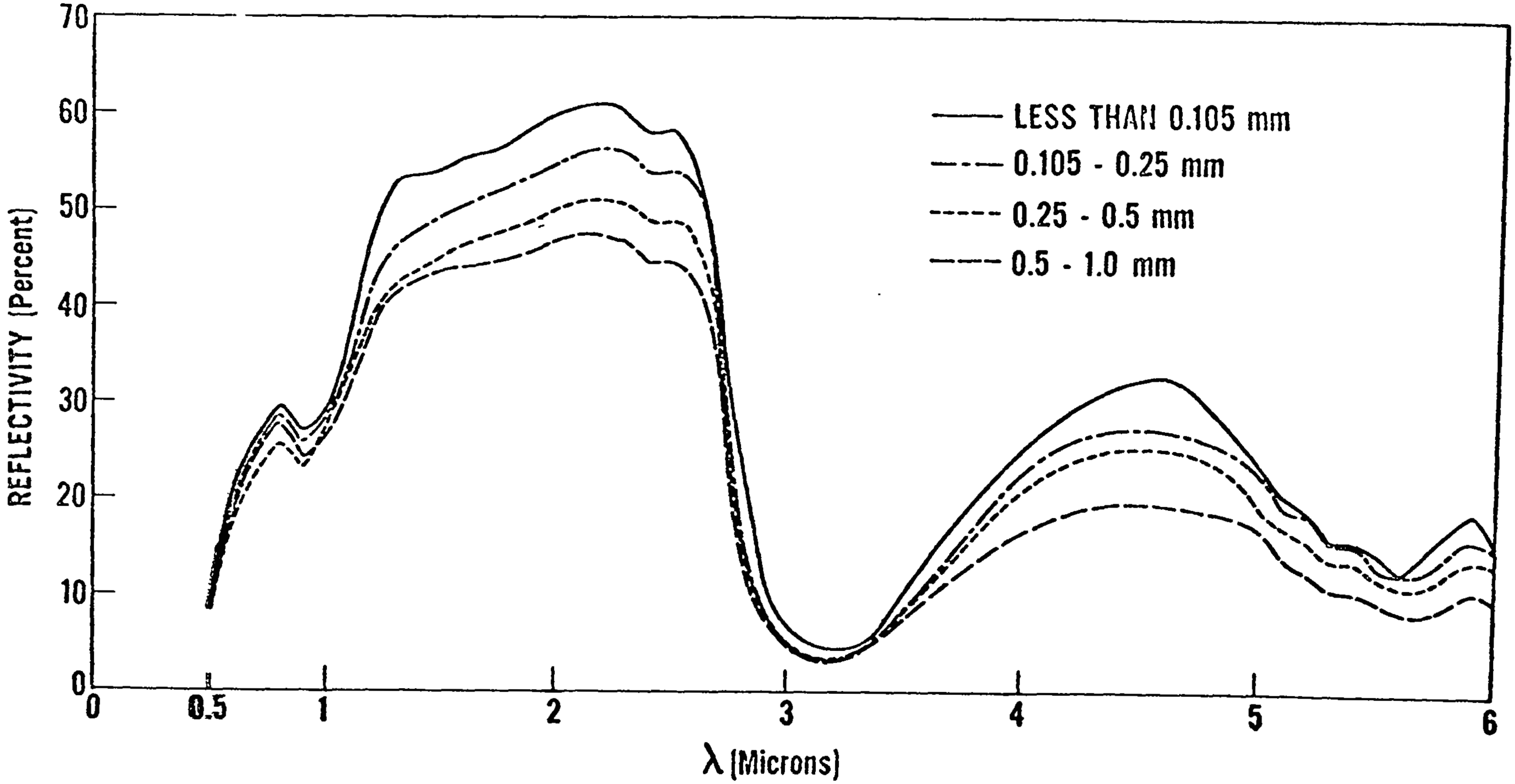


Fig. 24. The laboratory spectrum of pulverized limonite samples[45].

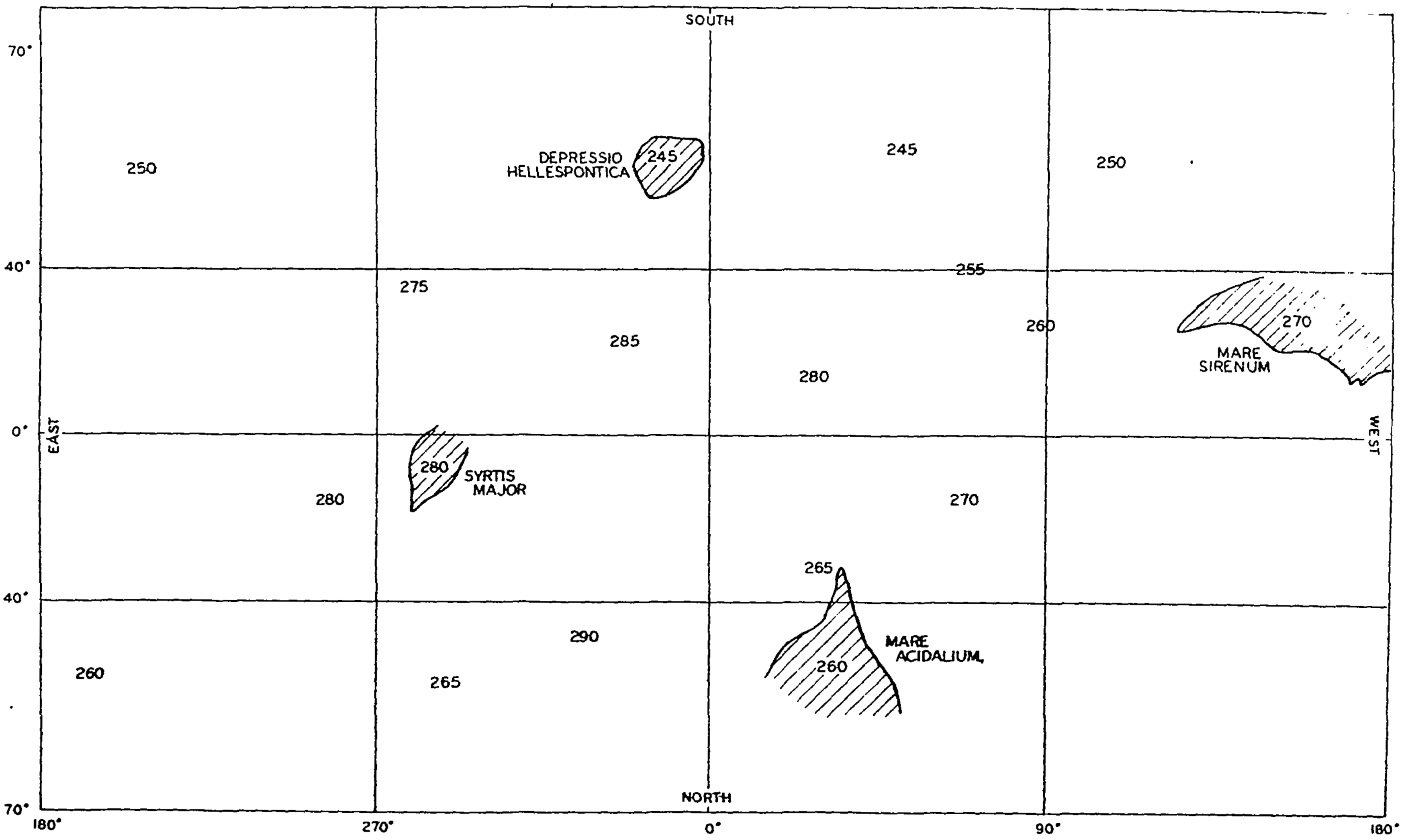


Fig. 25. Observed temperatures at the height of the darkening wave.

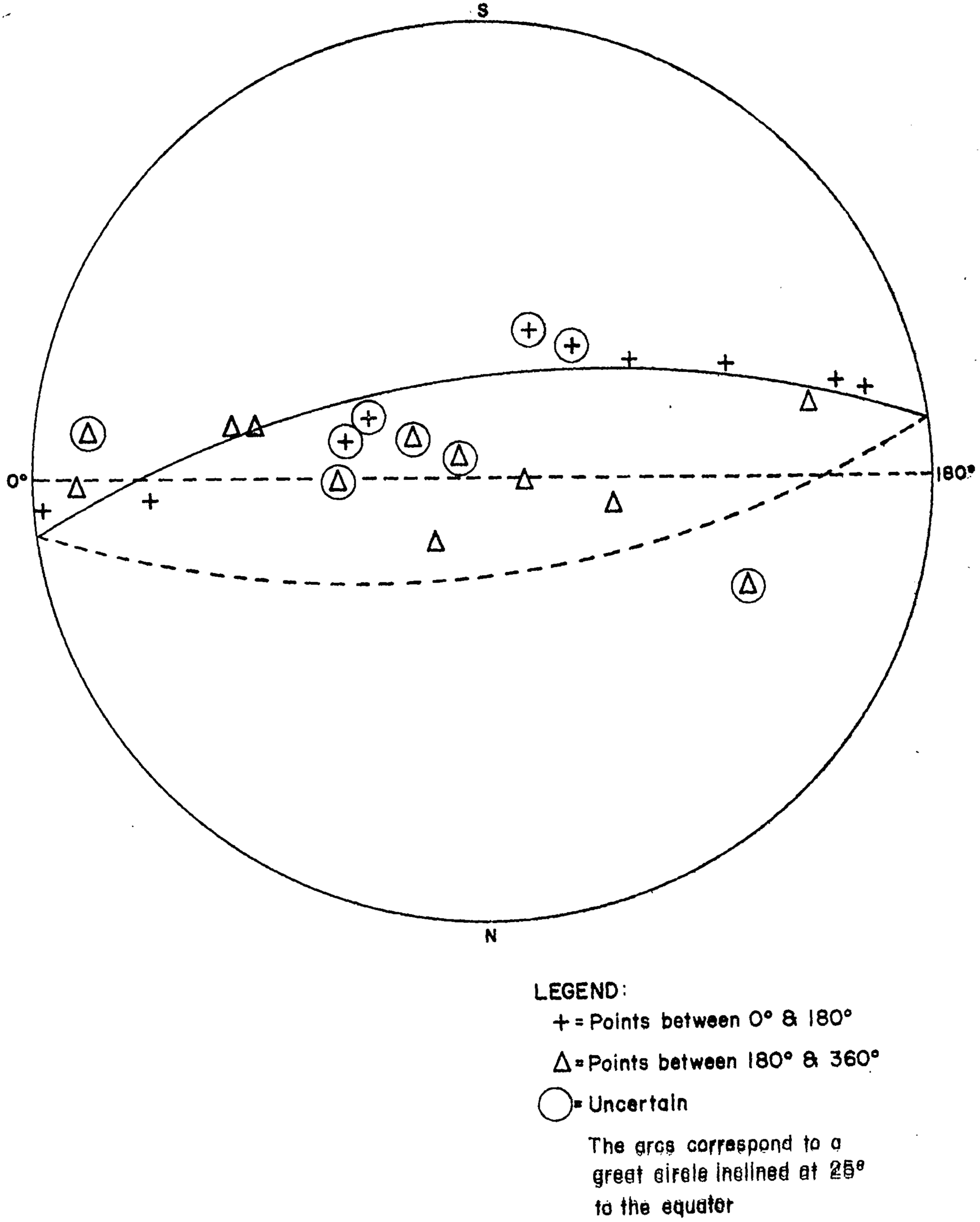


Fig. 26. A stereographic projection of presumed Martian volcanoes.