15 July 1966, Volume 153, Number 3733 **SCIENCE**

The Martian Surface

Craters larger than 20 kilometers have survived from the beginning; there never was a considerable atmosphere for any length of time.

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The interpretation of optical or radio observations of planets is usually ambiguous. Authors, guided by a single idea or by terrestrial analogies, reach conclusions which either cannot be proved or are contradicted by other evidence. Thus, from the reflectivity and polarization of the lunar surface, attempts have been made to identify the mineralogical composition. Yet experiments made at Cornell University have now shown that a great variety of mineral powders, whatever their composition, when blackened by corpuscular radiation, acquire optical properties almost identical with those of the moon if they consist of "needles" arranged in a "fairy-castle" fashion. Thus, while important conclusions on the geometrical setup of the lunar surface can be derived from optical studies, nothing can be told about the chemical or mineralogical composition.

The much more distant planet Mars may lead to even more dubious interpretations. The scarcity of observational material and lack of confirmation are here especially disturbing. The story of the infrared bands near 3.6 microns is very instructive in this respect. These bands were at first attributed to the CH bond characteristic of complex hydrocarbons and indicative of some kind of organic matter (*1*). Then it was shown that they fitted absorption bands of heavy water, HDO, much better (*2*). This led to speculations on the enrichment of deuterium on Mars, through preferential escape to space of the lighter hydrogen, or through other mechanisms (*3*). Finally, it turned out that the bands belong to heavy water in the terrestrial atmosphere and have no bearing on Mars (*4*).

Yet some conclusions are certain, or more certain than others. Thus, the mere presence of stray bodies in the solar system, in particular of asteroids crossing the orbit of Mars, leads to an unrefutable calculation of the probabilities of encounter with Mars and creation of impact craters (*5, 6*): "With the scarcity of water and lesser density of the Martian atmosphere, erosion should proceed there much slower than on earth; the traces of impact should stay at least for 10 million years and, perhaps, ten times longer than that, in which case the surface of Mars should be covered with hundreds of thousands of meteor craters exceeding in size the Arizona crater. It is not impossible that certain characteristic features of the Martian topography such as the spots called *lacus* or *lucus* may be related to past impacts of asteroids" (*7*). These rather obvious predictions somehow passed almost unnoticed; this explains the general surprise at the Mariner IV results (*8*), which showed craters more or less of the expected frequency (*9*): extrapolation of the Mariner IV crater counts (*8, 9*) down to a diameter of 1.2 kilometers (the size of the Arizona crater) yields an expected total of 250,000 over the entire Martian surface.

Attempts to ascribe a volcanic origin to the Martian features (*10*) can be ignored completely. Whether there are volcanic formations on the moon or Mars remains to be proved; some inconspicuous lunar objects are indeed suspected of being of volcanic origin. The lunar and Martian craters bear close resemblance to terrestrial meteor craters and are very different in structure from terrestrial volcanoes and calderas (*11*). Meteor craters are both an observational and a statistically predictable fact.

A different matter is the identification of the "oases" as major craters or the points of impact, and of the "canals" radiating from them as cracks in the Martian crust produced by the impact. This is only a hypothesis, and the nature, if not the reality, of the canals is questionable: "Disregarding the onetime acute controversy, we may maintain that the system of canals, whether regular or consisting of an agglomeration of spots, is undoubtedly real. . . . Possibly, they are cracks in the crust, produced by the impacts. The oases from which the cracks radiate might be remnants of meteor craters. If the soil is more fertile in the cracks, vegetation may develop there, rendering by its darker shade the oases and canals observable" (*12*, p. 281). Mariner IV covered too small an area at too close range to permit us to decide on these suggestions, and the "canals," apparently broad spotty features some 150 kilometers wide, are not conspicuous on the pictures yet are traceable on frames 2 and 3 (*9*).

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Major Surface Markings

On Mars there are two main types of markings—the orange, yellow, or reddish areas called *continentes* (singular, *continens*) accounting for about 70 percent of the total, and the dark areas or *maria* (singular, *mare*) covering about 27 percent of the surface. There are transition regions and small markings of darker shade, so that the relative areas cannot be assessed very accurately. The maria are sometimes described as greenish or bluish, but they are only less reddish than the continentes, of a brownish gray shade, occasionally "with a mere touch of moss-green in the equatorial regions; even this may be but a matter of visual contrast" (*13*). The shade and coloration change with the season. A third, highly variable type of surface marking is the polar caps, deposits of hoarfrost covering large areas in winter and almost disappearing in summer. There are no open bodies of liquid or frozen water on Mars.

Measurements of the infrared radiation around 10 microns, transmitted by the terrestrial atmosphere, indicate a large diurnal fluctuation of temperature in the top layer of Martian soil, much greater than that encountered anywhere on Earth and second only to lunar fluctuations. From observations in 1954 (*14*), when the planet was near perihelion, nearest to Sun and Earth, the temperature at the equator, tentatively corrected for imperfect emissivity (*12*, p. 282), was, at 7 a.m., −49°C; at 10 a.m., +17°C; at 2 p.m., +39°C (maximum). The nocturnal temperatures can only be guessed, and Fig. 1 represents the probable diurnal variation, with a minimum at dawn of −62°C, an amplitude of 101°C, and an average of −22°C for the warmest equatorial season. At average distance from the sun the mean equatorial temperature would be −28°C, and the mean of the globe, −42°C.

With the large diurnal amplitude and the tenuous atmosphere, the heat turnover at the Martian surface is essentially radiative. In daytime, most of the incoming heat is immediately radiated away and little is stored in the soil. The arithmetical average surface temperature, −22°C for the equator when the planet is at perihelion, is lower than the radiative gray-body average, −14°C, which equals the constant temperature at which the surface would radiate all the incoming heat. The large amplitude in temperature causes an asymmetry in the turnover of heat, 72 percent being radiated away between sunrise and sundown, and only 28 percent at night.

The temperature beneath the Martian surface is below freezing point to a depth of about 1 kilometer. One obvious conclusion is that any moisture in the Martian soil can only be in the form of permafrost. In view of the extreme dryness of the atmosphere and the scarcity of water, as indicated by the rapid disappearance of the polar caps in summer, there probably is no moisture in the soil, and most of the water is either in the atmosphere (about 0.0014 gram per square centimeter of the surface, or less than 1/1000th of the terrestrial value) or in the polar caps, alternately sublimating and evaporating.

On the other hand, the large diurnal amplitude indicates a very low thermal conductivity of the upper soil of Mars, about equal to that of atmospheric air, lower than that for terrestrial sand, and depending chiefly on the conductivity of the gas filling the space between the grains (*12*).

The daytime temperature in the maria was found to be higher, by about 8°C, than that of the continentes (*14*). This approximately corresponds to the greater absorptivity of the maria to solar radiation. A rocky surface of high conductivity would show a smaller amplitude—lower daytime and higher nocturnal temperatures. An excess of daytime temperature thus indicates a large diurnal amplitude in the maria, and hence that they are covered with a dusty unconsolidated top layer. The maria cannot be bare rocky surfaces from which the dust is blown away by the winds, a possibility suggested by Kuiper to account for their permanence (*15*).

Polarimetric observations (see *16*), though unable to tell the composition of the Martian surface, also show that the properties of the top soil in the maria and continentes are essentially similar, except that in the maria certain small, dark, and opaque objects seem to be added to the general orange background.

Mars is thus covered with a layer of dust and unconsolidated rubble, primarily produced by meteorite impact. The dust is often raised by storms, and its finest component seems to hang in the atmosphere over the entire surface. Blown about by the wind, it grinds the rock and produces more dust, as in terrestrial deserts. Aeolian (wind) erosion must be a powerful agent on Mars; it smoothes out differences in altitude, carrying away elevations, filling in depressions, and leading to migration of dust drifts all over the surface. From the statistics for Martian craters it can be concluded (*9*) that in 4.5 billion years a rocky elevation of up to 2 kilometers could be leveled out by erosion.

Against this background, the survival and apparent permanence of the Martian surface markings seem to suggest a certain regenerative property. Despite the dust storms, the maria are not covered with the uniform orange dust layer of the surrounding continentes, nor are the latter covered with the dark substance of the maria. Different chemical properties of the bedrock cannot be advocated as an explanation, for these differences would be soon neutralized by the immense amounts of dust.

Vegetation growing in favorable places on the drifting dust could serve as an explanation (*17*). Seasonal changes in the maria and the little dark objects of Dollfus seem to fit into the picture. That vegetation could survive the extreme cold and dryness of the Martian climate may seem incredible. Yet the very rigor of the environment may help in this respect: the nocturnal temperatures are so low that hoarfrost may be deposited (as is apparently observed) on the soil and hard-frozen plants; when this melts, drops of liquid water may be utilized by the plants while they are warming up in the morning sun (*12*).

This may sound hypothetical, to say the least; yet still more baffling are some remarkable changes, the biggest ever observed being the darkening of a continens region to the northeast of Syrtis Major or its virtual conversion into a mare. Around what could be called a "skeleton" system of dark markings—Toth, Nepenthes, Moeris Lacus—a vast dark region developed in 1954, tripling the area and increasing it by 1.2 million square kilometers (*18*). The development began in 1946 but did not become conspicuous until 1954. It persisted in 1956 and later. Though of lighter shade than the darkest maria (*12*, plates I and II), it was comparable to vast stretches of other "permanent" maria and appeared typical in this respect. Its boundaries remained essentially constant; only the shading changed.

The change was not seasonal and was the largest of its kind registered since 1840, when the first Martian map was constructed by Beer and Mädler. To an extraterrestrial observer, the changes produced by the Russian virgin-lands project in Kazakhstan would appear to be similar to this Martian change, and on a similar scale.

However doubtful the vegetation hypothesis of the maria may appear, it is difficult to find an alternative that accounts for all the facts.

Thus, it has been proposed that maria are elevated regions (*19*). In such a case, the darkish dust covering them and replenished by aeolian erosion must be continuously wandering into the "continental" lowlands, acquiring there the bright orange coloration through some chemical or irradiation process. Chemical action from underneath must be excluded because saturation would soon take place. Only continually renewed atmospheric reagents, such as carbon monoxide or oxygen (*12*), are possibilities. With about 40 centimeters of dust eroded in 1 million years (*9*) from the ridges and still partly staying there and remaining dark, the time for change of color must run into hundreds of thousands of years; during this period the dust would wander all over the Martian surface. Under this assumption the well-defined though not perfectly sharp mare borders would be incomprehensible—the transition from mare to continens takes place over less than 150 kilometers, as can be judged from photographs and photometry, and frame 8 of Mariner IV shows indeed a gradual transition from Zephyria to Mare Sirenum over a stretch of some 140 kilometers. The dust would be blown about over the entire surface before it changed color; not much diversity in color and shading could remain under such circumstances. Furthermore, despite the tenuousness of the atmosphere, the dust may be carried high by the winds; yellow dust storms are observed, such as one of hemispherical extent from 30 August to 5 September 1956, which covered all surface detail and, after clearing, left behind increased haziness and decreased contrast for months (*12*). The presumed "highlands" of the maria are thus open to the deposition of dust. If they are not covered with the same orange "paint" as the continentes, this must be due to some peculiar regenerative property. Plants shaking off the dust and growing on it would fit into the picture, while the hypothesis of lifeless, elevated ridges does not explain anything. The maria might be ridges (improbably, however), but this is beside the point and is unable to account for the persistence of their color and shading. The evidence of "leeward clouds" occurring on the maria borders (*19*) would appear rather dubious to anyone who has systematically observed the planet, and equally weak are the arguments that the maria are covered with volcanic ashes carried in persistent patterns by the prevailing winds (*20*).

Table 1. Transmission coefficient (p) and specific scattering of the Martian atmosphere (a), and reflectivity of the surface (s).

Wavelength (Å)	p	a	s
4600 (Blue)	0.33	0.20	0.25
5200 (Green)	.54	.22	.29
5430 (Green-yellow)	.60	.23	.34
5800 (Yellow)	.69	.24	.40
6400 (Red)	.74	.20	.53

Photometry and Spectral Behavior

The red color of Mars is the consequence of its generally low albedo (reflected fraction of light or reflectivity) decreasing toward the shorter wavelengths, from 0.33 in the extreme red (6900 Å) to 0.18 in the visual green-yellow (5550 Å) to 0.046 in the near-ultraviolet (3600 Å) (*21*). Hence the reflected light contains relatively more radiation in the red portion of the spectrum than the incident light. In the blue and violet the reflectivity is remarkably low and approaches that of soot.

In the green, yellow, and red the surface markings are visible, their contrast increasing with the wavelength. In the blue the maria become invisible, and they remain so in the shorter wavelengths. On photographs, invisibility begins at about 4420 Å; this margin fluctuates from 4260 to 4580 Å (*18*). If the disappearance of the surface details is due to absorption by a dusty or smoky veil, with absorption increasing toward the shorter wavelengths (*22*), the fluctuation of the spectral limit of visibility of detail can be attributed to a variation in the atmospheric dust content (*12*).

In the longer wavelengths Mars shows limb darkening, or a decrease of brightness toward the edge even at full phase. As with the full moon, the rough and dusty solid surface of Mars should appear uniformly bright; limb darkening is therefore an indication of an absorbing atmosphere. From an extended series of Russian observations of limb darkening, made with a small (6-inch) telescope (*23*), optical characteristics of the Martian atmosphere and surface were derived, as given in Table 1 (*12, 22*). The transmission coefficient is for one passage of the ray on a vertical path. The specific scattering of the atmosphere, a, determines its contribution to the surface brightness, which partly compensates for the loss through absorption of the light reflected by the surface. Without secondary scattering and for a single passage, p is the transmitted fraction, $a(1-p)$ the scattered fraction, and $(1-a)\ (1-p)$ the fraction of light absorbed by the atmosphere. The small

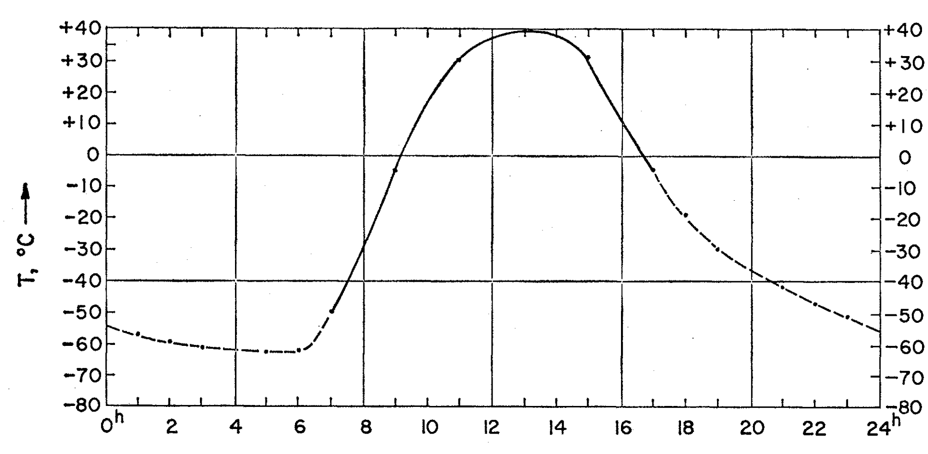

Fig. 1. Diurnal variation of surface temperature on the Martian equator at perihelion. (Ordinate) Temperature, in degrees Celsius; (abscissa) equivalent Martian hour. (Solid line) Observed temperatures; (broken line) extrapolated nocturnal temperatures. The maximum temperature is +39°C, the probable minimum at sunrise is −62°C for this warmest season. In winter, at 55° south latitude, the Mariner IV occultation indicated a daytime air temperature of −98°C, isothermal from surface to an altitude of 30 kilometers.

values of a and p indicate a dark, dusty atmosphere in which molecular (Rayleigh) scattering by the gaseous components is relatively small.

The photographic observations on which these results are based were made with a telescope of low resolving power; they were made when Mars was in opposition, near full phase angle ("full moon" phase), and their chief merit is their number, spread over several oppositions. Otherwise, systematic errors, due to lack of resolving power, are possible. No distinction was made between the maria and continentes, which must have introduced large accidental errors in the observed limb darkening.

In the blue and violet, limb darkening is absent, while patchy limb brightening occurs. This is compatible with an opaque atmosphere in which the scattered light is saturated and yields a uniform surface brightness in all directions. The low albedo is, in such a case, purely the albedo of the atmosphere itself and requires a specific scattering of $a = 0.15$, slightly less than in the green, yellow, and red (see Table 1). For comparison, a Rayleigh-scattering, gaseous atmosphere has $a = 1$, the light being scattered without true absorption. On Mars, only 15 percent of the violet light stopped by the atmosphere is truly scattered in all directions, while 85 percent is absorbed and converted into heat. If this picture of the atmosphere is correct, little ultraviolet light would reach the Martian surface; the dust, or aerosol smoke would efficiently protect the surface from biologically harmful radiation, fulfilling the role that ozone performs on earth. Because of the low value of a, there is not much multiple scattering and the radiation does not penetrate the atmospheric veil, either directly or indirectly. Less than 1 percent of the ultraviolet may get through, and the sun would look deep red on Mars even when it is near the zenith.

The results for the blue, as shown in Table 1, depend on the assumption that the disappearance of surface detail is caused by increased atmospheric absorption. Another possibility—that the difference in albedo of the Martian surface markings decreases toward shorter wavelengths, and may disappear in the violet—has been revived by Evans (*24*); undoubtedly some ambiguity exists in this respect.

Photometry of plates obtained in 1958 by R. S. Richardson and A. G. Wilson with the 60-inch reflector of Mount Wilson (*25*) helps to clarify this point somewhat. Figures 2 through 5 represent samples of normalized distributions of brightness along the optical equator, or the great circle passing through the subsolar point and bisecting the gibbous (terminator) limb. The continentes, the maria, and the transitional regions (bright maria, faint continentes, and borderline points) were identified from their coordinates and were treated separately.

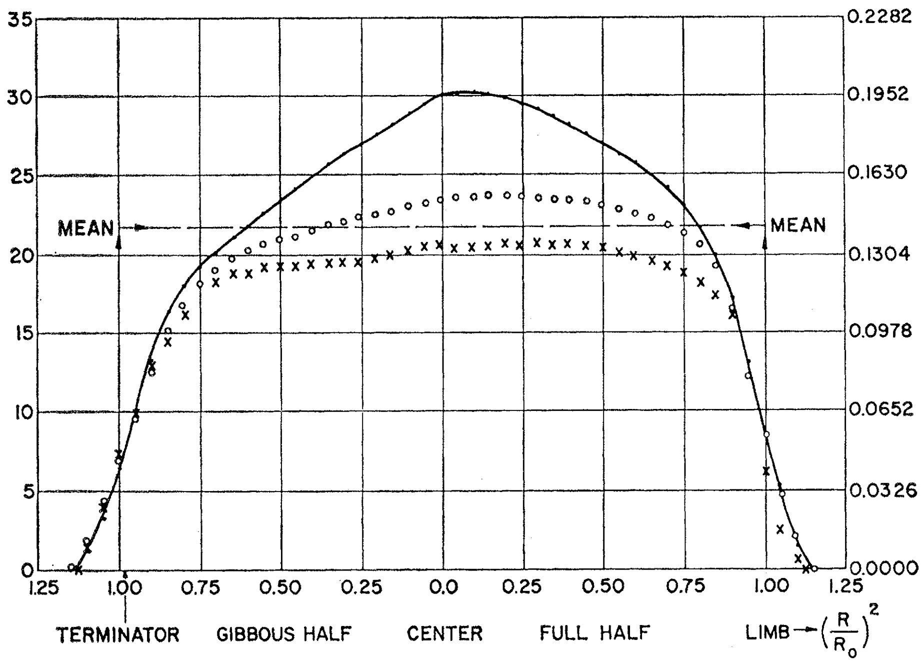

Fig. 2. Distribution of brightness along the Martian optical equator, yellow light (0.580 micron). From several exposures on two plates taken on 21–22 November 1958 with the 60-inch Mount Wilson reflector [R. S. Richardson and A. G. Wilson]. (Abscissa) Square of the relative radius (in units of R_0, the limb radius); (ordinate) surface-brightness arbitrary units (scale at left) and Lambert albedo units (scale at right). (Dots and solid curve) continentes; (crosses) maria; (open circles) intermediate or transitional points. Phase angle, 5 degrees (as for the moon 10 hours before full phase). Central meridian longitude, 197° and 226°. Subsolar point in latitude 12° South (advanced summer in southern hemisphere). Angular diameter, 18.5 seconds of arc. The mean surface brightness, equal to total light over limb area, is indicated.

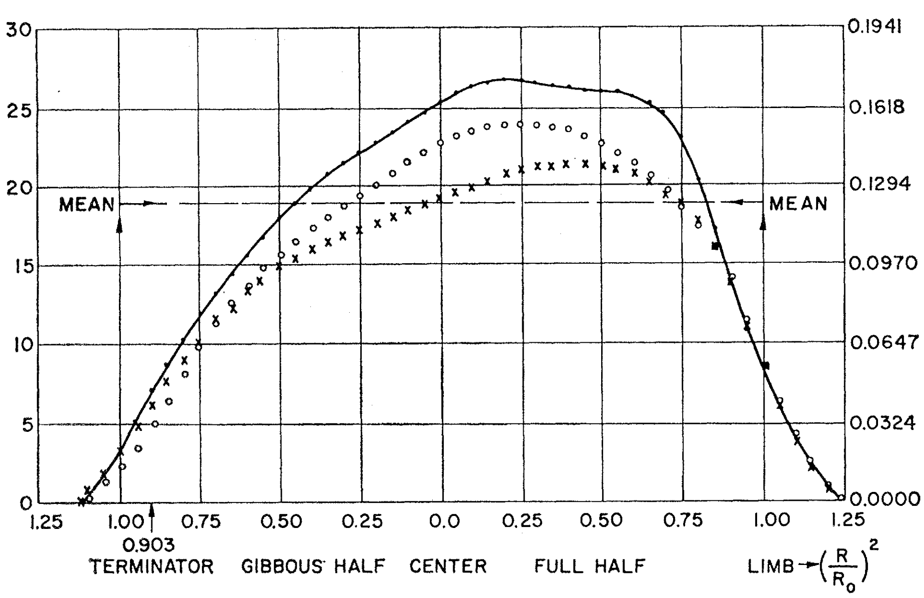

Fig. 3. Distribution of brightness along Martan optical equator, yellow light (0.580 micron). From several exposures on a plate taken on 7–8 December 1958 with the 60-inch Mount Wilson reflector [R. S. Richardson and A. G. Wilson]. Designation as in Fig. 2. Phase angle, 18 degrees (as for the moon 36 hours before full phase). Central meridian longitude, 42°. Subsolar point in latitude 9° South (late summer in southern hemisphere). Angular diameter, 16.5 seconds of arc.

Remarkable was the good agreement of different points for the same type of surface markings in yellow light, especially for the maria whose single points deviated from the mean curve by only ± 5 percent. The continentes showed about 3 times this dispersion. Apparently, at the time of observation in November 1958, the maria surfaces were very uniform all over the Martian globe, a somewhat surprising result in view of the obvious differences in shade which they present to the eye. On the other hand, the surface brightness of the continentes showed considerable variation. Perhaps the apparent differences in the darkness of the maria are due to contrast with the adjacent continentes—near an excessively bright continens a mare may look darker than the average.

The Mariner IV photographs covered too small a fraction of the Martian surface to give us a complete picture of the variety of Martian surface detail. They covered continentes and maria, without showing any decisive difference between them. The photometric uniformity of the maria is even more of a puzzle on this account. The Mariner IV close-up photographs reveal extreme spottiness in the Martian surface detail which is completely different from the large-scale detail observable from Earth. The entire surface seems to consist of small bright and dark elements, with linear dimensions from 10 to 100 kilometers. Apparently, the maria contain more of the dark elements than the continentes, possibly to near saturation, which may be the cause of their photometric uniformity. The continentes may contain a mixture of the bright and dark elements in different proportions, whence comes the greater unevenness in their surface brightness.

In Figs. 2 through 5 no correction has been made yet for the smearing-out of surface brightness caused by atmospheric unsteadiness and plate grain. The correction is not essential except at the very limb. The "Lambert albedo units" of brightness (Figs. 2–5, scale at right) show the ratio of the observed surface brightness to the mean surface brightness of a totally reflecting disk (albedo 1.000), at the given phase angle, whose spherical surface scatters uniformly in all directions according to Lambert's law; these are essentially absolute reflectivity units.

In the yellow (Figs. 2 and 3), the continentes-maria difference decreases from the center toward the limb, indicating atmospheric absorption. Unsteadiness in the surface brightness of the continentes undoubtedly affects the solution for the optical parameters. From the difference alone, Fig. 2 yields $p = 0.56$ and Fig. 3 gives $p = 0.89$; the average is 0.72, close to the value of p in Table 1 at 5800 Å; a value of a of about 0.4, higher than that in Table 1, is indicated. In Fig. 2, at $(R/R_o)^2 =$ 0.75, or 60° from the center, the low contrast on the gibbous half (to the left) is caused by the new mare regions which developed near 260° longitude and which were classed as continentes on traditional maps. The flat run of the curve for the maria indicates that the loss through absorption is nearly compensated by the atmosphere-scattered light, while the loss over the brighter continentes is not compensated and leads to the bulge in the curves.

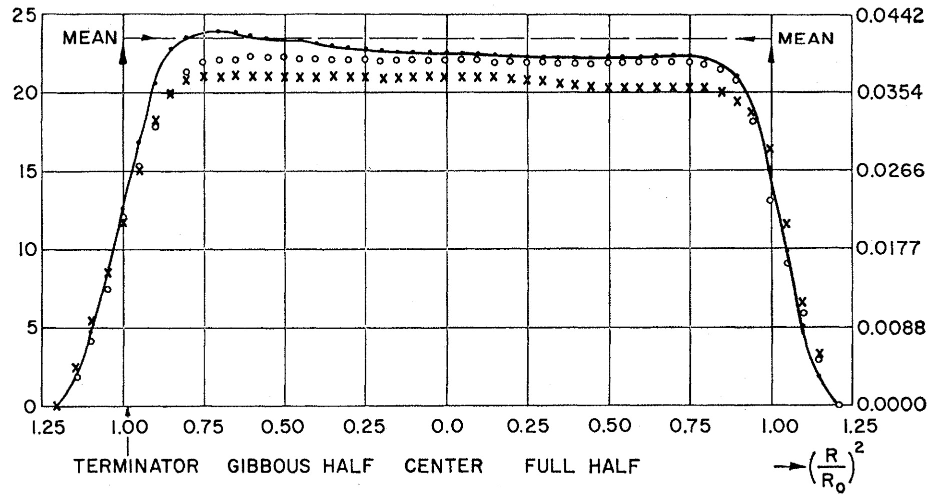

Fig. 4. Distribution of brightness along Martian optical equator, blue light (0.420 micron), 21–22 November 1958. Specification as in Fig. 2. Central meridian longitude, 200° and 229°. The north-polar limb brightening is not used in the curves, but is included in the mean brightness of the disk, which puts it accordingly higher than the mean of the curves.

In the blue (Figs. 4 and 5), quite unexpectedly, there is still some difference between the maria and the continentes, about 5 to 7 percent, which the eye fails to see on the photographs, yet which is revealed "blindfold" by the photometer. Irregular bright spots, especially near the limb, even lead to some limb brightening (Fig. 4, gibbous half, to the left) and make the curves somewhat uncertain. On Fig. 4, the continentes-maria contrast in the blue amounts to 0.0026 in albedo units, as compared to 0.062 in the yellow (Fig. 1); the contrast is reduced 25-

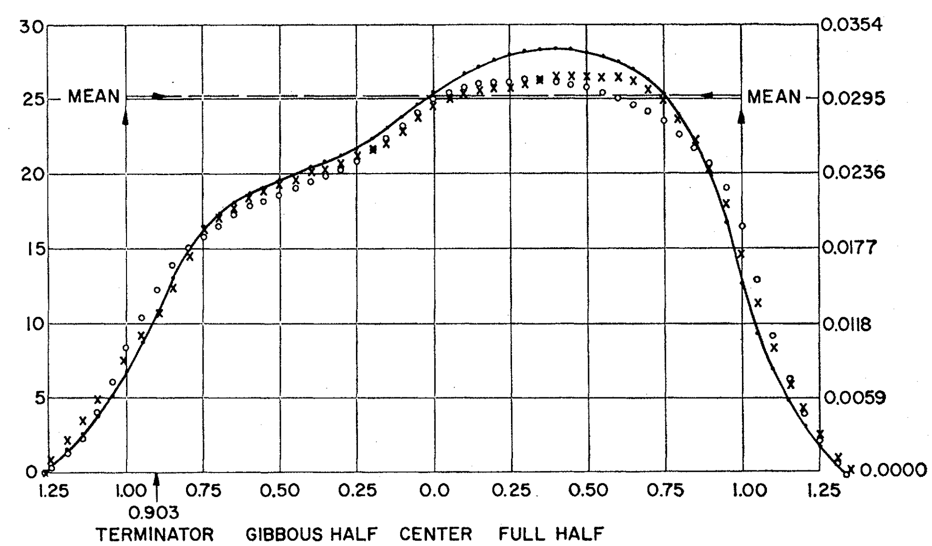

Fig. 5. Distribution of brightness along Martian optical equator, blue-violet light (0.400 micron), 7–8 December 1958. Specification as in Fig. 3. Central meridian longitude, 50°. Limb brightening used as in Fig. 4.

Table 2. Observed frequency (N_o) of craters larger than D in Mare Imbrium per 465,000 square kilometers, as compared with the calculated frequency (N_c) accumulated during 4.5×10^9 years; crater diameter (rim to rim) to projectile diameter ratio = 20.

D (km)	N_o	N_c	N_o/N_c
$\geq$ 1.19	733	1050	0.70
$\geq$ 2.48	208	202	1.03
$\geq$ 5.40	35	35	1.00
$\geq$12.7	10	5.0	2.0
$\geq$34.3	3	0.44	7
$\geq$70.6	1	0.10	10

fold. If this were entirely due to atmospheric absorption, a transmission coefficient of about $p = 0.2$ would be indicated at 0.420 micron, to be compared with $p = 0.12$ as tentatively suggested by the analysis (*23*); if there is some weakening of intrinsic contrast between the surface markings, the transmission coefficient will be larger.

A clue to the dilemma—either strong atmospheric absorption or negligible intrinsic contrast between the surface markings in the blue and violet—can be found in the bright marginal regions, chiefly around the poles, which appear on the blue-violet photographs. These are usually interpreted as some kind of transparent cirrus clouds, floating at a higher level above the dusty absorbing layer. If this interpretation were correct, some veil and decrease of contrast should be observed also in the yellow or red. This, however, is not the case, and there is increased contrast at these places in the longer wavelengths, as seen on photographs taken by W. H. Wright on 29 July 1939 (*12*, plate IV) and also on the photographs of 21–22 November and 7–8 December 1958, discussed here (*25*). A strong polar cap, reaching from the north pole to about 35° northern latitude, was the most prominent feature on the blue plates. Yet, over Mare Acidalium the cap was about 1.4 times fainter than over the adjacent continens Tempe; this is the same proportion as that for a typical mare relative to a continens on a yellow plate on which Mare Acidalium appeared in full contrast, without veiling and without the trace of any "cap" being present.

The absolute surface brightness of the cap, 1.5 to 2.0 times the average, was only about 0.03 for the mare and 0.04 for the continens, in albedo units, on 7–8 December and 0.07 for the continens (Cebrenia) on 21–22 November. This is about 25 to 40 percent of the reflectivity in the yellow. Clearly, in the blue the "bright" polar cap was intrinsically quite a dark formation, appearing bright only by contrast with the still darker rest of the surface.

From these considerations a strong case can be made against the cirrus cloud hypothesis of the blue polar brightenings or "false polar caps." Instead, these brightenings seem to be areas of greater atmospheric transparency where the real surface is shining through. Around the Martian poles, especially in winter, anticyclonic high-pressure regions establish themselves, similar to those over Siberia and Canada but more stable. The downward atmospheric motion purifies the air, carrying downward and equatorward the dust or smoke. A similar effect could be obtained at night, producing bright areas at sunset or sunrise, as observed.

Distinct from these blue marginal brightenings, there are of course real polar caps, visible in the yellow. They belong to the surface and exhibit the well-known seasonal changes.

It seems, thus, that the intrinsic contrast between the Martian surface markings is about the same in the blue as it is in the yellow and red, and that the lack of visible detail in the blue is caused by the absorbing veil of a dust-laden atmosphere.

Craters and Erosion

There has been a series of papers in which the authors have tried to estimate the age of the Martian craters. Only one of these (*26*) applies first-hand collision theory; the others (*27*, *28*) deal, so to speak, with second-hand relative crater frequencies. But even Anders and Arnold, despite their empirically correct Monte Carlo calculation of collision frequencies, use partly the moon as a standard for absolute calibration; they find that the observed number of Martian craters is several times smaller than expected and that therefore their age must be about 800 million years, or but a fraction of the total span of 4.5 billion years during which the planet was subject to the bombardment of interplanetary stray bodies. The other authors (*27*), using the moon as a standard, also arrive at low ages of a few hundred million years, while one obtains up to 2.2 to 3 billion years (*28*). The latter figure still requires intense erosion during a prolonged early stage of the planet's history.

Table 3. Cumulative frequency of diameters larger than d of the Mars asteroids.

d (km)	Observed number	Probable number	
		$s = 1.6$	$s = 2$
68	1	1	1
34	5	5	5
17	11	15	20
8.5	22	45	80
4.2	31	135	320
2.1	32	405	1,280
1.05	33	1,215	5,120
0.52	34	3,645	20,240

These conclusions entirely depend on using the moon as an absolute standard for calibration. The comparison is made for the large craters of diameter in excess of 20 kilometers; the lunar maria carry an excess number of such craters (*29*), as compared with that expected from collisions in 4.5×10^9 years. There is no good reason to transfer this excess to Mars, where the conditions may have been different.

Without using absolute numbers, there is a check on the role of erosion, based on the frequency law of crater diameters. From the theory of hypervelocity impact (*30*), supported by experiment, crater diameter is proportional to projectile diameter (for a given average velocity and specification of materials). Hence the empirical power law for the frequency of diameters of stray bodies (meteorites, asteroids, comet nuclei) applies also to the frequency of impact craters:

$$N = D^{-s} \times \text{const.} \qquad (1)$$

where N is the cumulative number per fixed area of craters whose diameters are in excess of D, and s is the "population index." This index keeps more or less constant over a wide range of diameters. As stated, the same equation applies to projectile diameters, of course with a different constant. Or, simply, there is a certain average ratio of crater diameter (D) to projectile diameter (d),

$$D/d = A, \qquad (2)$$

so that d can be substituted for D in Eq. 1.

For asteroids in the diameter range of 2–90 kilometers, $s = 1.59$; for comet nuclei, $s = 2.1$; for lunar craters in Mare Imbrium between 1.14 and 34.3

kilometer in diameter, $s = 1.64$ (*29*).

Unless there is erosion, the population index of craters and projectiles will be identical. For craters which have survived erosion from the very beginning, a more or less constant population index, $s \sim 1.6$ to 2.1, can be expected.

Now, erosion can be assumed to carry off a certain fixed layer thickness from a protruding object, such as a crater wall, in a unit of time. This especially applies to aeolian erosion or grinding by dust storms, and to meteoritic erosion. Hence a crater wall will survive for a length of time that is proportional to its height or depth, and this in turn is proportional to crater diameter. The upper limit of age, or the time of accumulation of small craters on a dust-blown surface, is thus proportional to crater diameter; for a steady rate of accumulation of impact craters, the numbers will be proportional to time of survival. Thus an additional factor D enters Eq. 1 for eroded craters,

$$N_e = ND = D^{-(s-1)} \times \text{const.} \quad (3)$$

The population index is now, by one unit, less, and is expected to lie between $s - 1 = 0.6$ and 1.1.

From the data of Leighton *et al.* (*8*), for $D > 20$ kilometers the frequency of Martian craters can be represented by a constant value $s = 1.71$ (*9*), close to the expected value for non-eroding craters. Hence, without calculating the absolute frequency of impacts, one may conclude that craters on Mars larger than 20 kilometers have not been completely eroded, and that some must have survived the entire span of the 4.5-odd billion years since the surface of the planet was formed.

Below 20 kilometers the population index of the Martian craters decreases (*8*). Because of integration for different sizes, the decrease from s to the asymptotic value $s-1$, though rapid, must be gradual, so that over the transition range of diameter a value between $s-1$ and s should hold. Indeed, between $D = 9$ and $D = 20$ kilometers, for which the counts seem to be complete, the frequency curve of Martian craters, while bending down, attains an average of $s = s_1 = 0.97$, thus approaching but not quite reaching the limiting value $s - 1 = 0.71$.

While for Mars the ultimate erosion limit for crater size is $D_0 = 20$ kilometers, the frequency of craterlets on the Ranger pictures shows a kink at $D_0 = 0.30$ kilometer (*31*), which comes near the prediction by Öpik, $D_0 = 0.20$ kilometers, based on micrometeorite erosion (*29*). Despite their apparent vagueness, it seems that the estimates of erosion are on safe ground. The relative rates of erosion in terrestrial deserts (erosion of Egyptian sphinxes), on Mars, and on the moon are then in the ratio of 2000: 70:1 (*9*). A crater of 1-kilometer diameter would last 7 million years in a terrestrial desert, 200 million years on Mars, and 14 billion years, or three times the age of the solar system, on the moon. These are upper limits of age, proportional to crater diameter, signifying the time needed to erase completely all external traces of a crater. Erosion should work faster with fresh craters; therefore, for most of the time the craters will be strongly eroded, with low walls, as actually is manifested by the Martian craters. Of course, these numerical estimates are rough and only serve to describe the order of magnitude. Yet the mere presence of the kink in the Martian frequency curve offers strong support to the hypothesis that craters larger than 20 kilometers have survived from the time when the surface of Mars was formed, and that during all this time the rate of erosion was never excessive over periods longer than 10^8 years.

Craters and Collision Frequency

Without unjustified proportionality factors linking the lunar and Martian crater frequencies, the theory of close encounters with the planets (*7, 32*) and of hypervelocity impact (*30*), together with the known or estimated frequency of stray bodies in the inner solar system (*33*), leads to direct estimates of the crater impact frequency which are valid above the erosion limit—20 kilometers for Mars, 0.3 kilometer for the moon. The uncertainties of the numerical data and theory may amount to +100 percent or −50 percent. Table 2 represents a check on the lunar Mare Imbrium, for which the calculated frequencies for the smaller craters agree with observation even better than expected (*29*), in view of the complete independence of the two sets of data. The calculated number is for uniform incidence during the entire time of 4.5 billion years. The main contribution is from comet nuclei, and a constant rate of incidence of these objects is compatible with their storage and survival in "Oort's sphere of comets" at the outskirts of the solar system, until stellar perturbations send some of them toward the earth's vicinity, where they can be observed. The sphere suffers little depletion with time and thus represents a source of steady supply.

These results for the moon serve to prove the validity of the direct method of calculation of the frequency of craters. Without the need of using the observed lunar crater frequencies, the method can be applied directly to Mars in the expectation that the results will be as reliable as for the moon. With respect to the population of stray bodies, there is a difference, however. Comet nuclei and the Apollo type "asteroids," which in all probability are but extinct comet nuclei (*32, 34*) which represent the main and steady source of impacts on the moon, are of but secondary importance for Mars. Its main source is a group of asteroids swarming around the planet and crossing its orbit ["crossing" means that the two orbits have a common range in heliocentric distance, without necessarily intersecting; actual intersection takes place after intervals of the order of 10^5 years, as the consequence of secular perturbations (*7*)]. A considerable fraction of these asteroids have survived from the "beginning" because Mars, with its small mass, is but gradually eliminating them; yet their numbers are steadily decreasing with time, in a ratio of $e = 2.718$ to 1 during a time interval equal to the expectation of life, as given in the column 4 of Table 4.

There are 34 known Mars asteroids, with diameters from 1.8 to 89 kilometers; because of observational selection, the smaller members are recorded but incompletely, and the list mainly refers to the large objects. Table 3 gives the observed distribution of their diameters, as well as the probable number corrected for observational selection (*32*) by assuming two different values of the population index: $s = 1.6$, the most probable value—that for the bulk of the asteroids and for lunar craters—and $s = 2$ as an upper limit. The difference between the two last columns of Table 3 conveys an idea of the uncertainty of extrapolation. Of asteroids with diameters smaller than 4 kilometers, only three have been actually observed; these are exceptional objects which may come close to earth because

Table 4. Selected members of the Mars group of asteroids.

Name	Estimated diameter (km)	Impact velocity (km/sec)	Life expectation (10^9 yr)	Probability of ultimate collision with Mars	Impact rate on Mars per 10^{10} yr
Long-lived members					
132 Aethra	89	13.3	24.5	0.958	0.38
475 Ocllo	35	11.8	20.5	.929	.45
1036 Ganymede	59	16.7	16.4	.981	.60
1134 Kepler	6.6	11.8	11.1	.932	.84
1310 Villigeria	28	12.8	17.5	.949	.54
Short-lived members					
433 Eros	20	8.6	1.84	.795	4.3
985 Rosina	14	7.1	3.68	.647	1.8
1131 Porzia	8.7	7.0	2.87	.638	2.2
1198 Atlantis	5.2	7.4	1.84	.684	3.7
1204 Renzia	13	7.0	3.17	.647	2.0

of their orbital characteristics; at the distance of Mars they are fainter than the 17th magnitude and virtually unobservable.

Table 4 contains estimates and calculations for a few characteristic samples of the Mars asteroids (*32*). Column 3 gives the impact velocity on Mars as the quadratic sum of the encounter velocity and the planet's velocity of escape (5.0 kilometers per second); column 6 gives the normalized impact rate per individual, as corresponding to its orbital elements.

Two typical groups are represented in Table 4. The long-lived members, with high impact velocities, contribute little to the cratering frequency and, at the same time, their ultimate collision chances (column 5) are high. Three of those listed have been used by Anders and Arnold (*26*) to determine the relative collision frequencies with Mars and the moon, yet, because of the low impact rates, they are not representative. The short-lived, with low impact velocities and high impact rates, actually determine the outcome.

Taking all the listed Martian asteroids as individual representatives of the population, from the theory of encounters (*32*) the probable number of their parent population was found equal to 93.3, of which 44.8 must have collided with Mars and 14.5 must have been deflected to terrestrial crossings and there rapidly removed, leaving the balance of 34 listed survivals (*9*). The short-lived are removed more rapidly, and their original population (of objects with small eccentricity and inclination) must have greatly prevailed. Setting the lifetime limit at 4.5×10^9 years, 4.5×10^9 years ago there must have been 56.6 short-lived and 36.7 long-lived members, as compared with the present ratio of 10 to 24. Objects with still shorter lifetimes—that is, with smaller eccentricities and inclinations—which were in the beginning operative in building the planet may by now have disappeared completely; this extinct component of the asteroidal population may account for the observed excess of the Martian crater numbers over those calculated on the basis of the presently surviving asteroidal population.

In Table 5 the directly and independently calculated frequencies of craters on Mars and the moon (*9*) are compared with observed frequencies (*8*). For the Mars asteroids, $s = 1.6$ was assumed (see Table 3).

Table 5. Calculated number of noneroded craters larger than 20 kilometers produced per 10^6 square kilometers in 4.5×10^9 years by impacts from the presently known populations of stray bodies, as compared with observed numbers. The number of impacts by the Mars asteroids allows for the depletion of their population with time.

Source of impacts	Mars			Lunar maria		
	Calculated number	Observed number*	Observed/calculated	Calculated number	Observed number†	Observed/calculated
Nuclei of "live" comets	1.26	—	—	1.77	—	—
Apollo-type objects (extinct comet nuclei)	0.55	—	—	0.79	—	—
Mars asteroids	7.0	—	—	.10	—	—
All	8.8	36	4.1	2.66	20	7.5

* See *8*. † See *29*.

Contrary to what has been found by other authors applying indirect methods, the observed number of craters on Mars turns out to be in excess of the calculated number in a ratio of 4 to 1. If $s = 2$ is assumed for the Mars asteroids (see Table 3, column 4), the calculated total number of Martian craters larger than 20 kilometers (asteroids larger than 1.4 kilometer) would be increased to 31, nearly matching the observed number. In any case, the directly calculated theoretical crater frequencies do not indicate any excess as compared to the observed numbers. Within a generous margin, allowing for the uncertainty in the extrapolated numbers of small asteroids, there is no ground for assuming the existence of a massive atmo- and hydrosphere, and intense erosion for any prolonged period in the planet's early history.

The excess in the lunar crater numbers for the maria can be explained by the larger pre-mare craters having survived flooding (presumably by lava, caused by large asteroidal impacts). The smaller craters have been completely erased, which would explain why their calculated numbers agree with those observed (Table 2). In the lunar continentes all the pre-mare or *primeval* craters have survived.

On Mars, the survival of some primeval craters, imprinted during the last stages of the formation of the planet from planetesimals, may account for the observed excess. Nevertheless, the crater density on Mars is much less than in the lunar continentes (if such generalization can be made from counts covering only 0.5 percent of the planet's surface). This indicates that, immediately after the saturation cratering (within the first 100 million years or so) which gave the finishing touch to the planet, either intense erosion must have leveled out all the primeval markings or a few large asteroids colliding with the planet melted enough rocks to flood the surface, in the same manner as in the case of the lunar maria, but on a larger scale. Large planetesimals, less subject to drag by the surrounding medium, must have a tendency to survive longer (*35*), descending on the planet during the finishing stage and erasing the smaller primeval craters. This is the case with the lunar maria. And, indeed, on the Mariner IV pictures—frames 7, 8, 11, 14, and others—one can see traces of almost erased giant "ghost craters" 200 kilometers or more in diameter. The later craters, imprinted on this background, plus those surviving from the primeval stage, reasonably agree with the expected number of impacts during the subsequent 4.5 billion years.

As already mentioned, one reason for the excess in the number of Martian craters might have been the complete removal of a class of ultra-short-lived objects, those planetesimals with nearly circular orbits which built the planet. In the list of 34 Martian asteroids, there is none with a lifetime shorter than 1.8×10^9 years. Yet, if there were originally a population numbering 100 of similar-sized objects, but with a lifetime as short as 800 million years, only a fraction of 0.004 of them, or 0.4 individuals, would have been expected to have survived until now; the absence of such objects in our list can therefore be readily explained by natural selection.

Whatever the explanation, the excess of the Martian crater numbers would imply that most of them are very old, certainly older than 3000 million years. This would agree with their low crater walls and their apparently advanced stage of erosion (*8*).

The possibility cannot be excluded that Mars, in the beginning, during a few hundred million years had more water and air, most of which subsequently escaped to space. However, it would be wrong to think that this would signify conditions agreeable to the development of life. Clouds, snow, and ice would reflect and deprive the planet of a considerable fraction of solar heat. Climatic theory (*36*) leads to the conclusion that, on a watery planet like our earth, a decrease of solar radiation below 88 percent of the present value would lead to a global ice age, including the tropics, and with all oceans frozen. Mars receives only 43 percent of the terrestrial input of solar radiation; an abundance of water on that planet would mean water only in the form of ice and snow, and a mean global temperature of $-62°C$, equal to the lowest winter temperatures of eastern Siberia or the Antarctic. If life has ever developed on Mars, it could have started only when most of the water evaporated to space.

A noticeable source of the Martian atmosphere must be the outgassing of the surface layers due to asteroidal impact. According to the formulae of hypervelocity impact (*30*), an average asteroid of 3-kilometer diameter, at a velocity of 10 kilometers per second, would penetrate about 7 kilometers deep into the Martian crust, producing a giant explosion, an instantaneous volcano, and a crater 40 kilometers across and demolishing a mass of rock 100 to 150 times its own mass. Only about 4 percent of the Martian surface may be pockmarked with craters which survived during the past 4.5 billion years; yet it may be assumed that gas was released and retained from the top layer of the crust several kilometers deep, which was battered by the last incoming planetesimals while the surface had cooled down and the gas was no longer lost immediately to space. With a gas content of the crust the same as for some meteorites, this would yield 100 to 200 grams of carbon dioxide per square centimeter and several times more water. This is more by an order of magnitude than the Martian atmosphere contains and would allow for losses through escape to space and chemical surface reactions. It seems thus that, without any true volcanism, this atmosphere may be entirely due to gases exhaled by the top layer of the crust, broken up by asteroidal impacts.

Table 6. Drift velocities of dust particles in the Martian atmosphere.

Radius of particles (cm)	Velocity (cm/sec)
10^{-2}	128
10^{-3}	2.3
10^{-4}	0.14
10^{-5}	.014

Yellow Dust Clouds

Besides the permanent smoky veil of aerosols in the Martian atmosphere there have been observed sporadic events of extended yellow clouds or haze, lasting for days or weeks and longer. Thus, from 30 August to 8 September 1956, a yellow cloud of almost hemispherical extent covered much of the southern hemisphere so that even the southern polar cap became temporarily invisible (see *12*, Lick Observatory photographs, plate II). Kuiper thought that a new polar cap emerged from under the cloud, and found it "remarkable that this event occurred shortly before the summer solstice" (*13*). However, inspection of the photographs shows that no new cap was formed, but that the old cap, somewhat diminished in size as befits the season, emerged from under the cloud cover. The densest portion of the cloud seems to have started over Mare Sirenum, covering half of this feature on 30 August and extending then over an area 600×1000 kilometers (*13*). Having spread over an area of the order of 3000 kilometers across, most of its substance seems to have cleared within about 10 days, though even a month later I observed the atmosphere to have appeared unusually hazy and the contrasts reduced (*12*, Fig. 6.1).

On 16 January 1950, an "explosion" over Mare Chronium (58°S) was reported by T. Saheki in Japan (*5, 37*), an experienced observer; a gray cloud of unusual color spread on the limb to a length of 1500 kilometers.

Both events took place in high southern latitudes, one in midwinter, the other in the Martian midsummer. These events do not seem to be linked to seasonal or geographic ("areographic") causes; hurricanes or tornadoes whirling up the dust could account for them, but the homogeneous surface structure, without open bodies of water and contrasting dry land, and the low density of the atmosphere could hardly lead to such freak events in odd places. Volcanic eruptions (*20*) are a still less attractive proposition.

The size of the dust particles involved can be estimated from the settling time, around 10 days for the bulk of the dust in the 1956 event. With 10 to 20 kilometers as the approximate altitude, the settling velocity is of the order of 2 centimeters per second. For an atmospheric density of about 2×10^{-5} gram per cubic centimeter and carbon dioxide as the main constituent (*38*), the molecular mean free length of path is 10^{-3} centimeter, not small as compared to the dust radii. The Stokes-Millikan formula yields then the drift velocities of the dust particles, as given in Table 6.

It appears that particle radii of 10^{-3} centimeter yield the right order of velocity (this depends little on atmospheric density); these particles may represent the bulk of the dust cloud, with smaller particles accounting for the long-enduring aftereffect.

Asteroidal impact may be considered another possible cause of the dust veils (*5*). Most efficient is the smoke produced by the explosion of the so-called central funnel of the crater, about 40 times the mass of the meteorite (*30*). Assuming all this mass to be converted into smoke particles of 10^{-4}-centimeter radius, we probably overestimate the screening efficiency and underestimate the required mass.

An area 1500 kilometers across covered by a single layer of the 10^{-4}-centimeter particles requires 4×10^{12} grams of smoke or 10^{11} grams ($= 10^{5}$ tons) of a projectile—an asteroid 38 meters in diameter. Extrapolation of the asteroid frequencies of Table 3 with $s = 1.6$ would yield only one collision of this kind or greater in 15,000 years—clearly too rare an event to be considered seriously.

However, extrapolation of the numbers with a constant population index cannot be very reliable. In the process of planet formation from a cloud of planetesimals or asteroids, before the process was completed mutual collisions among members of the cloud may have increased the number of small fragments at the expense of the larger ones. It is therefore not impossible that the number of small asteroidal fragments around the Martian orbit is greater indeed. Meteorites with $s = 3.3$ and meteors in direct elliptical or "asteroidal" orbits with $s = 4.2$ (*29*) both show a steep increase of numbers with decreasing size. Assuming an intermediate value of $s = 3.8$ for the smaller Martian asteroids, the number of those larger than 38 meters is greatly increased, leading to one collisional event in 6 years. This would more or less correspond to the observed frequency of the yellow-veil phenomena.

It is thus not impossible that the yellow dust clouds are caused by impacts of numerous smaller members of the Martian group of asteroids (*5*). Although this conclusion is subject to considerable doubt, it is the most attractive of the explanations and invites special asteroidal studies of the conventional astronomical type, with the largest Schmidt-type telescopes, in a search for the faintest members of the Martian group, to verify their actual numbers.

As to the volcanic theory of the dust-cloud events, it is made especially improbable by the thinness of the Martian atmosphere. The atmosphere of Mars, like that of Earth, can only be the result of exhalation from the crust, and its amount is a measure of past plutonic activity. Nitrogen, as a nonreacting and nonescaping constituent (*12*), is a measure of the total release of gases over the planet's history. On earth, free nitrogen amounts to 800 grams per square centimeter of the surface. On Mars, the total amount of the atmosphere derived from the occultation of Mariner IV (*38*), 13 to 16 grams per square centimeter, is close to the amount of carbon dioxide determined spectroscopically (*39*). Not much is left for the other constituents. The occultation took place at 55° southern latitude near Mare Chronium in winter, at solar altitude 20 degrees, and the scale height, 9 ± 1 kilometers, indicated a constant temperature of about $-100°C$ up to an altitude of 30 kilometers. The isothermacy and the low temperature are more or less what could be expected for continental winter daytime conditions, similar to those of eastern Siberia. Any noticeable admixture of nitrogen would make the temperature incredibly lower. An upper limit to the amount of nitrogen and to volcanic activity would thus put it at 1/200 the terrestrial. With Krakatoa-, Katmai-, or Agung-type explosions happening perhaps once in a decade, similar explosions could be expected on Mars but once in several thousand years. As mentioned before, the thin atmosphere accumulated on Mars can be accounted for by asteroidal impacts alone, so that volcanic activity must be even less intense than is estimated here.

Summary

With the scarcity of factual data and the difficulty of applying crucial tests, many of the properties of the Martian surface remain a mystery; the planet may become a source of great surprises in the future. In the following, the conclusions are enumerated more or less in the order of their reliability, the more certain ones first, conjectures or ambiguous interpretations coming last. Even if they prove to be wrong, they may serve as a stimulus for further investigation.

Impact craters on Mars, from collisions with nearby asteroids and other stray bodies, were predicted 16 years ago (*5–7*) and are now verified by the Mariner IV pictures.

The kink in the frequency curve of Martian crater diameters indicates that those larger than 20 kilometers could have survived aeolian erosion since the "beginning." They indicate an erosion rate 30 times slower than that in terrestrial deserts and 70 times faster than micrometeorite erosion on the moon.

The observed number, per unit area, of Martian craters larger than 20 kilometers exceeds 4 times that calculated from the statistical theory of interplanetary collisions with the present population of stray bodies and for a time interval of 4500 million years, even when allowance is made for the depletion of the Martian group of asteroids, which were more numerous in the past. This, and the low eroded rims of the Martian craters suggest that many of the craters have survived almost since the formation of the crust. Therefore, Mars could not have possessed a dense atmosphere for any length of time.

If there was abundant water for the first 100 million years or so, before it escaped it could have occurred only in the solid state as ice and snow, with but traces of vapor in the atmosphere, on account of the low temperature caused by the high reflectivity of clouds and snow. For Martian life there is thus the dilemma: with water, it is too cold; without, too dry.

The crater density on Mars, though twice that in lunar maria, is much smaller than the "saturation density" of lunar highlands. Many *primeval* craters, those from the last impacts which formed the planet, must have become erased, either by late impacts of preferentially surviving large asteroids or by a primeval atmosphere which rapidly escaped.

The tenuous Martian atmosphere may have originated entirely from outgassing of surface rocks by asteroidal impacts, which also could have produced some molten lava. The role of genuine volcanism on Mars must have been insignificant, if any.

The large amplitude in temperature indicates that the Martian upper soil, equally in the bright and the dark areas, is of a porous unconsolidated structure, with a thermal conductivity as low as that of atmospheric air.

Limb darkening at full phase in green, yellow, and red light indicates absorption by atmospheric haze, aerosols, and dust. The loss of contrast in the blue and violet is caused by stronger absorptivity of the haze, which is almost as dark as soot, and not by a true decrease in contrast of the surface markings. Photometric measurements in the blue reveal a residual contrast of 5 to 7 percent between the markings in 1958, invisible to the eye at a time when there was no "blue clearing."

The surface brightness of the maria was surprisingly uniform in 1958 (late summer in the southern hemisphere), while the continentes showed considerable variation. In view of the spotty microstructure of the Martian surface as revealed by Mariner IV, and the lack of a sharp border between a mare and a continens, it seems that all the difference consists in the relative number of small dark and bright areas in the surface mosaic.

If there is vegetation on Mars, it should be concentrated in the dark-area elements, measuring 10 to 100 kilometers. Vegetation is the best hypothesis to account for seasonal changes in the maria and for the persistence of these formations despite dust storms of global extent. Survival of vegetation in the extreme dryness of the Martian climate could depend on the low nighttime temperature and deposition of hoarfrost, which could melt into droplets after sunrise, before evaporating. If not vegetation, it must be something specifically Martian; no other hypothesis hitherto proposed is able to account for the facts. However, the infrared bands which at one time were thought to be associated with the presence of organic matter, belong to heavy water in the terrestrial atmosphere.

The conversion of a former bright area into a dark one in 1954, over some 1 million square kilometers, is the largest recorded change of this kind. Even on the vegetation hypothesis, it eludes satisfactory explanation.

Relatively bright areas observed in the blue and violet in polar regions and elsewhere on the limb can be explained by a greater transparency of the atmosphere, its dust content being decreased by a downward (anticyclonic) current. The surface, of a greater reflecting power than the atmospheric smoke, then becomes visible.

The sudden explosion-like occurrence of yellow or gray clouds, reducing atmospheric transparency and surface contrast, could be due to impacts of asteroids; in such a case, however, the number of unobservable small asteroids, down to 30 to 40 meters in diameter, should greatly exceed the number extrapolated from the larger members of the group. A "meteoritic" increment in numbers, instead of the asteroidal one, would be required. Special observations with large Schmidt telescopes could settle this crucial question.

The Martian "oases," centers of "canal" systems, could be impact craters. The canals may be real formations, without sharp borders and 100 to 200 kilometers wide, due to a systematic alignment of the dark surface elements. They may indicate cracks in the planet's crust, radiating from the point of impact.

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