Reports

Ultraviolet Reflectivity of Mars

Abstract. *Ultraviolet spectrograms of Mars (2400 to 3500 angstroms, ~50-Å resolution) have been obtained with an objective grating spectrograph on an Aerobee rocket. The data indicate a reflectivity of 0.04 to 0.08 in the ultraviolet, increasing toward shorter wavelength according to a Rayleigh Law. The data can be represented by a model having an atmosphere of nitrogen, carbon dioxide, and argon, and a surface pressure of about 5 to 20 millibars. The photographic appearance of the planet in the blue is interpreted as a loss of surface contrast and reflectivity rather than an absorption in the atmosphere by the "blue haze." The model permits prediction of the general appearance of the planet in the photographic ultraviolet, blue, visible, and red. There are serious biological implications since the model suggests that ultraviolet radiation (2000 to 3000 Å) will reach the surface.*

On 19 March 1965, 0300 U.T., several spectrograms of Mars were obtained with an objective grating spectrograph launched from White Sands Missile Range aboard Aerobee NASA 4.57 GG. The camera used in the instrument was designed and manufactured by the Kollmorgen Corporation. It has an effective focal ratio of $f/2.11$, an effective focal length of 70 mm, and can be described briefly as being a modified, wide-field, reflecting microscope objective. It is equipped with spherical, aluminized surfaces; is nonvignetting; and has a calcium fluoride corrector plate. The plane diffraction grating used was 10 cm square with 600 lines per millimeter. A "best fitting" cylindrical film surface was matched to the spherical focal surface of the spectrograph. Eastman Type I-O, 35-mm roll film was used to investigate the spectrum of Mars, from 2350 to about 4500 Å. Exposure times for the eight spectrograms were alternately 10 and 46 seconds, except that the last was 35 seconds. The elements of Mars at the time of observation were: true distance from earth, 0.674 AU (astronomical units); distance from the sun, 1.659 AU; semidiameter, 6.95 seconds of arc; phase angle, 8.14°; illuminated fraction, 0.995. The values used for the distribution of solar energy are based on published information (*1*, *2*).

The spectrograms were analyzed with a modified Joyce-Loebl microdensitometer-isophotometer; chromatic abberations in the spectrograph and aberations introduced by a cylindrical film surface fitted to a spherical image surface were corrected by use of the standard microdensitometer and isophotometer features. The Mars spectrogram contains the spectrum of β Leo which has beeen used for an in-flight calibration of the instrument. There is excellent agreement between the stellar calibration of the flight spectrograph and laboratory calibration of three identical spectrographs. The spectrum of β Leo has also been used to determine absolute values for the reflectivity of Mars. Values for the ultraviolet spectral intensity of β Leo have been based on the theoretical distribution of intensity of an A3V star, with a Blue minus Visual color index of + 0.09 and an apparent visual magnitude of 2.10, corrected for spectral absorption features (*3*). The data are presented in terms of geometric reflectivity (that is, compared to a Lambert scattering plane surface), rather than of spherical albedo, and apply to the integrated disc of the planet. The resolution of the spectrograms is approximately 50 Å, as determined by the profile of the solar magnesium absorption features at 2800 Å. At this resolution, there are no features in the spectrum which can be attributed to chemical absorptions; thus, the atmosphere can only be analyzed by interpreting the general characteristics of the spectrum.

The best spectrogram is reproduced in Fig. 1. The values which have been derived for the reflectivity of Mars are reproduced in Fig. 2. The limits of error on the derived reflectivity values appear to be less than a factor of 2 (decreasing toward the visible) for the relative reduction, and slightly less for the absolute determinations derived by comparison to β Leo. The error limits refer to the degree of confidence in the best spectrogram. They are not quantitatively derived. The geometric reflectivity values determined by ground-based observers and summarized by deVaucouleurs (*4*), and the 2700-Å value determined by Boggess and Dunkelman (*5*) from data transmitted from a rocket flight in 1957 are also reproduced in Fig. 2.

The curve of relative values for the geometric reflectivity of Mars (Fig. 2) is adjusted to the ground-based value of 0.04 at 3500 Å. The absolute values were determined and plotted without regard to the relative value. There is extremely close agreement of these two methods in producing reflectivity values between 2500 and 3000 Å.

In order to derive a value for the optical depth and therefore for the surface pressure of the Martian atmosphere from the observed reflectivity spectrum, the atmospheric scattering properties and surface reflectivity of Mars must be considered.

Values for geometric reflectivity for model atmospheres with Rayleigh scattering can be derived and compared to the Martian ultraviolet spectrum. Reflectivity values for a plane parallel atmosphere with Rayleigh scattering for 0.0, 0.25, and 0.80 surface reflectivity have been computed (*6*). The reflectivity values of a spherical atmosphere can be approximated by placing a plane parallel atmosphere tangent to each point of the surface. Because of the low reflectivity of Mars in the 3000- to 4000-Å region of the spectrum, the model with zero surface reflectivity was chosen. Table 1 represents the integrated geometric reflectivity values from a planet with a Rayleigh scattering atmosphere, zero phase angle, and zero surface reflectance for seven different optical depths. In order to assign wavelengths to the various optical thicknesses, it is necessary to compute the Rayleigh scatter-

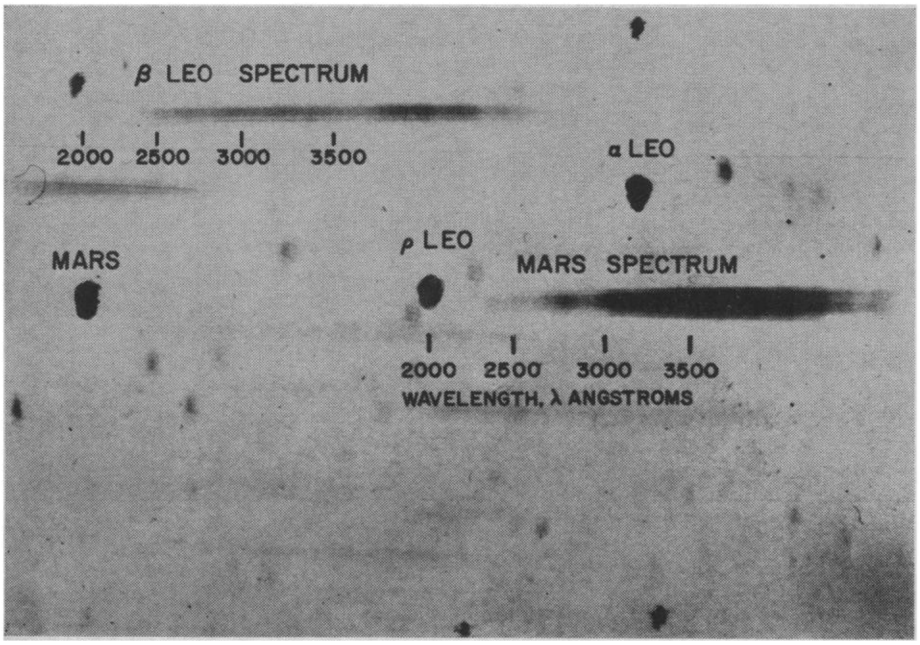


Fig. 1. Mars spectrogram. The zero order image and spectra of Mars are contained within the spectrogram. The spectrum of β Leo is present, with the zero order image outside the film format. The peculiar shape of the zero order images is due to rocket motion during the 45-second exposure. There is noticeable contrast loss in the reproduction below 2800 Å.

ing properties of model atmospheres. This work has been done by Coulson and Lotman (*7*) for a model atmosphere of Mars having a composition of 94 percent of N_2, 4 percent of A, and 2 percent of CO_2, with a surface pressure of 85 mb. They present their results in terms of normal optical depth versus altitude for wavelengths above 2000 Å. By selecting their results for different altitudes, it is possible to determine the scattering properties of atmospheres with surface pressures from 4 to 85 mb for an atmosphere consisting mainly of nitrogen.

At any specific wavelength there is a relation which exists between optical thickness, τ; index of refraction, n; number of particles per unit volume, N; molecular weight, m; and the derived surface pressure, P_s, for any combination of Rayleigh scattering particles. The relation, reduced to its simplest form, is

$$P_s\,(CO_2) = P_s\,(N_2) \times \frac{(n_{N_2}-1)^2}{(n_{CO_2}-1)^2} \times \frac{m_{CO_2}}{m_{N_2}} = 0.68\,P_s\,(N_2), \quad (1)$$

and is approximately independent of wavelength in the spectral region being considered. The relation betweeen surface pressure, composition, and optical depth is presented in Table 2.

From Table 2 it is possible to determine values of geometric reflectivity as a function of wavelength (Fig. 3). The reflectivity of Mars in the ultraviolet can therefore be interpreted in terms of surface pressure.

The amount of CO_2 in the atmosphere of Mars is approximately 45 m-atm (*8–10*). This corresponds to a surface partial pressure of CO_2 of about 3 mb. Since the atmosphere is thin, the reflectivity of the constituents will be directly additive. Therefore, the reflectivity from sources other than CO_2 is almost identical with the curve for N_2 at 9 mb for geometric reflectivity below 3000 Å. If N_2 is the major remaining constituent and all the reflectivity is due to Rayleigh scattering, then the total surface pressure will be about 12 mb. The error introduced by instrumental calibration and data reduction is about ± 5 mb for this total pressure.

There are several factors which can influence the value determined for surface pressure by the scattering technique. Any contributing reflectivity from clouds, haze (*11*), or the surface will lower the reflectivity attributed to Rayleigh scattering, and thus decrease the proposed pressure value. If the "blue haze" were an absorbing layer (*12, 13*), or opaque reflecting layer, the Rayleigh reflectivity would represent a pressure at the top of this layer. If there were absorbing components such as N_2O_4 and NO_2 in the atmosphere, distributed with altitude which prevented ultraviolet radiation from reaching the surface, then the derived pressure value would be a lower limit for the surface pressure.

The ultraviolet spectral profile supports the idea that the atmosphere is transparent in the ultraviolet. There are no detectable absorption features in the 2400- to 3500-Å region, indicating that there are no significant amounts of ultraviolet absorbers such as ozone or a mixture of N_2O_4 and N_2O (*14, 15*) in the atmosphere. This indicates that the "blue haze" is not an absorbing component of the atmosphere.

In the ultraviolet, it is likely that the reflectivity of the surface must be at least 0.01 or 0.02 since naturally occurring substances are not usually black in that region of the spectrum. Even gold black and carbon suspended in oil reflect significantly in the ultraviolet, 0.003 (*16*). The reflectivity of most naturally occurring materials found on earth, especially rocks and large scale landscapes (not necessarily including vegetation) decrease from red to blue, being generally lower than 0.1 by 4000 to 4200 Å, especially desert regions (*17, 18*). The reflectivity of the moon is about 0.06 (*19*) in the photographic ultraviolet. It would not be unreasonable to expect the ultraviolet reflectivity of the surface of Mars to be in the 0.01 to 0.02 range. Besides indicating a low reflectivity for Mars, by comparison with the earth and moon, there is the simultaneous inference that the contrast of surface features will be reduced, and easily obscured by any reflectivity due to the atmosphere above the surface. Thus, a major portion of the featureless appearance of Mars in the ultraviolet can be explained by a loss of reflectivity and contrast of the features themselves.

This does not, however, preclude the presence of actual hazes or clouds of large particles. In fact, the "blue-clearings" do indicate the presence of such a haze (*13, 17, 20*). The haze would be required to be very thin and tenuous because the total reflectivity of the planet in the 3000- to 4000-Å region of the spectrum is only ~0.04. The amount of water present in clouds of 0.01 to 0.02 reflectivity, if the clouds are indeed aqueous, would be well below the limit of detectability from earth (*8, 10, 21–23*). The data are therefore not inconsistent with water clouds. The Martian clouds should be easily observable when the surface reflectivity dropped to ~0.05 or less. They

Table 1. Geometric reflectivity from a spherical planet with Rayleigh scattering; zero phase angle; zero surface reflectivity.

Normal optical thickness (τ)	Integrated reflectivity
0.02	0.014
.05	.033
.10	.064
.15	.095
.25	.137
.50	.235
1.00	.367

should be observed mainly in photographs in the blue and ultraviolet, since it is in those spectral regions where the surface reflectivity is low. Surface features of low reflectivity and contrast would be further obscured by such a haze or cloud, even if the haze had a very low reflectivity. Features of high reflectivity, 0.10 to 0.20, in the blue and photographic ultraviolet should be observed in the photographs of the planet, even through the thin haze. The polar cap, a snow or frost feature, has this high reflectivity and is observed in blue and ultraviolet photographs (*13, 17, 20*).

The derived pressure range of 10 to 20 mb is likely to be an upper limit because the atmosphere appears to be relatively transparent, as indicated by low reflectivity and absence of absorption features in the ultraviolet, combined with the visibility of the polar cap in blue and ultraviolet photographs. A lower limit cannot be definitely assigned because the exact values of reflectivity of the surface and the "blue haze" are not known. The reflectivity of 0.04, at 3400 Å, consists mainly of reflection from the surface and the haze. The haze reflectivity should change slowly with wavelength and the surface reflectivity is likely to decrease toward shorter wavelengths. A realistic value of the non-Rayleigh reflectivity at 2500 Å would be about 0.02. The lower limit for the pressure values would then be about 5 to 15 mb, 10 mb being most likely. The values are summarized in Table 3.

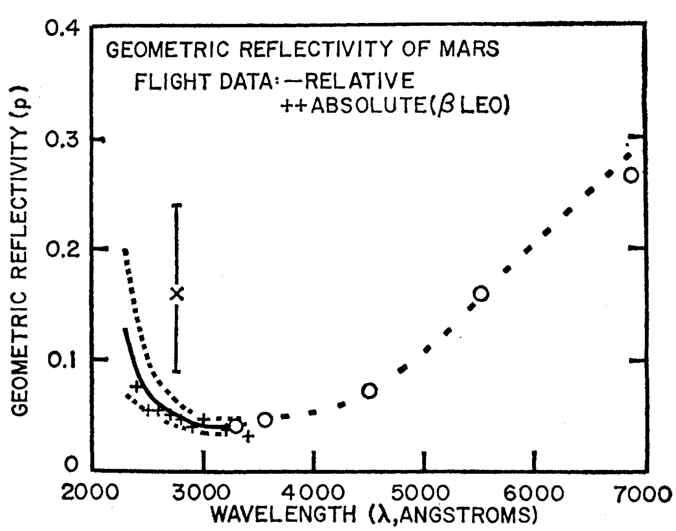
From calculations based on the Rayleigh-scattering tables (*6*), the central reflectance due to scattering from a 10-mb atmosphere should be about 0.01 and the limb reflectance should be about 0.05 in the 4500- to 5000-Å region. At shorter wavelengths the center-to-limb contrast due to Rayleigh scattering should decrease while the limb reflectivity should steadily increase to 0.10 or 0.15 (in the photographic ultraviolet). Also, the polar cap should become less distinct in the ultraviolet owing to loss of contrast, (that is, the atmospheric reflectivity equals or exceeds the reflectivity of the polar cap). This effect can apparently be seen in published photographs of Mars (*17, 20*). In the red, a gradual limb darkening is inferred by similar calculations from the tables of Rayleigh scattering. This darkening occurs because the surface reflectivity is high in the red regions. The effect of the atmosphere at the limb is the scattering of light from the observational path instead of increasing the brightness, as in the case of low surface reflectivity. The limb should be slowly darkened, rather than be dark just at the edge. Again, this effect is apparent in the

Table 2. Correspondence of wavelength and optical thickness: Rayleigh-scattering atmosphere, zero phase angle, zero surface reflectivity.

Normal optical thickness, τ	Wavelength (Å) at various surface pressures* A	B	C	D	E
0.02	2650	3300	4000	4800	5600
.05	2150	2650	3250	3900	4500
.10	<2000	2250	2750	3300	3800
.15		2025	2500	2950	3450
.25		<2000	2200	2625	3050
.50			<2000	2200	2600
1.00				<2000	2200

* Surface pressures: A, 3 mb CO_2 or 4 mb N_2; B, 6 mb CO_2 or 9 mb N_2; C, 14 mb CO_2 or 21 mb N_2; D, 31 mb CO_2 or 45 mb N_2; E, 58 mb CO_2 or 85 mb N_2. For argon surface pressure multiply N_2 pressure by 40/28.

data accumulated from observations (*17, 20*). The scattering due to a thin haze will cause similar effects, but computations of the effect have not been made. The surface reflectivity and total reflectivity of Mars is highest in the red region of the spectrum. It is relatively safe to assume that the reflectivity of the polar cap is a constant and not a function of wavelength (by comparison to H_2O, CO_2, and similar "frosts" on the earth). The contrast between the "light areas" and the polar cap will be decreased in the red region. Limb darkening in the red will tend also to reduce the contrast. Since the predictions based on a model having 10- to 20-mb surface pressure are borne out by observed characteristics from ground-based observations, the credibility of the low pressures is improved. Recent work by other experimenters indicates that pressures of 10 to 20 mb



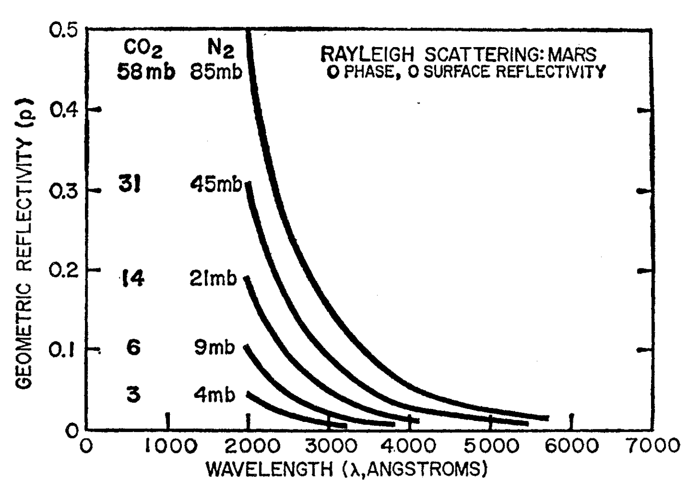


Fig. 2 (left). The geometric reflectivity of Mars. Solid line, relative data adjusted to 0.04 at 3400 Å; **+**, absolute reflectivity determined by comparison with β Leo, plotted independently. The dashed lines below 3400 Å represent the error range applied to the relative data. Open circles, data from ref. (*4*); **x**, data from ref. (*5*). Fig. 3 (right). Geometric reflectivity of model atmospheres of Mars as a function of wavelength and surface pressures; see text for details.

Table 3. Possible composition of the Martian atmosphere calculated from the ultraviolet reflectivity.

Amount (m-atm at 0°C, 1 atm)			Surface pressure (mb)
Pure CO_2	Pure N_2	N_2 (with 45 m-atm CO_2)*	
66	104	32	5 lowest limit
132	208	136	10 most probable
198	312	240	15
274	416	344	20 highest limit

* Data from ref. *8–10*.

would apply to the surface of Mars (*8, 9, 10, 24*). The determination of pressure by Kaplan, Munch, and Spinrad (*10*) is based on photographic infrared spectrograms, and thus can be attributed to the surface since the atmosphere is transparent in that spectral region.

The spectrum of Mars can be divided into several regions where different effects are important in producing the reflectivity of the entire planet. Below 3000 Å, Rayleigh scattering, large-particle scattering, and reflection from the surface are all important, with Rayleigh scattering beginning to predominate at shorter wavelengths. In the 3000- to 4000-Å range, Rayleigh scattering should contribute about 0.01 to the total reflectivity, large-particle scattering 0.01 to 0.02, and surface reflectivity about 0.01 to 0.02. The reflectivity of the polar cap should be approximately constant at all wavelengths at about 0.15 to 0.25 (that is, slightly higher than the light areas in the red region of the spectrum). The contrast of surface features should be reduced essentially to zero in the 3000- to 4000-Å range. Maximum limb brightening should occur at 4500 to 5000 Å owing to Rayleigh scattering. Between 4000 and 5000 Å, the increasing reflectivity of the surface should begin to predominate in determining the total reflectivity. The contrast of surface features should rapidly become apparent. Above 5000 Å, where the reflectivity of the surface predominates, limb darkening should become apparent. All of these effects can be observed in photographs of the planet Mars.

The appearance of the planet in different colors can be satisfactorily described without postulating atmospheric absorbers in the blue and ultraviolet. The 10-mb model can be used to determine the ultraviolet flux at the surface of Mars. If there is a ten times larger than possible oxygen concentration of 70 cm-atm (*8*), the model permits inference that the transmission of direct solar radiation to the surface, at 60° solar zenith angle, will be about 70 percent at 2000 Å (correcting for both scattering and oxygen absorption). Between 2000 and 3000 Å, approximately 90 percent of the direct solar radiation should reach the surface. There will be serious biological effects caused by such high-intensity radiation. Studies of the germicidal effects of ultraviolet radiation (*25*) indicate that a lethal exposure to the radiation would be accumulated in 1 or 2 days for almost all types of bacteria, spores, fungi, viruses, protozoans, and so forth found on earth.

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Merrihueite, A New Alkali-Ferromagnesian Silicate from the Mezö-Madaras Chondrite

Abstract. *Merrihueite, a new mineral with the approximate chemical composition $(K,Na)_2(Fe,Mg)_5Si_{12}O_{30}$, occurs with iron-rich olivine, iron-poor pyroxene, and nickel-iron in a few chondrules of the Mezö-Madaras chondrite. The refractive index lies between 1.559 and 1.592; the birefringence for each composition is low to moderate. X-ray powder data for merrihueite are nearly identical to those for osumilite, $(K,Na,Ca)(Mg,Fe)_2(Al,Fe)_3(Si,Al)_{12}O_{30}{\cdot}H_2O$, and very similar to those for synthetic $K_2Mg_5Si_{12}O_{30}$. Merrihueite is interpreted as an alkali-ferromagnesian silicate mineral of the osumilite type. It is named in honor of the late Craig M. Merrihue, meteoriticist, of the Smithsonian Astrophysical Observatory.*

The Mezö-Madaras chondrite, an unequilibrated, low-iron, ordinary chondrite (*1*), contains a few chondrules made up of the unusual mineral assemblage: clinoenstatite, fayalitic olivine, nickel-iron, and a new alkali-ferromagnesian silicate mineral. This assemblage will be described and discussed in detail elsewhere. The purpose of this report is to announce the new mineral, for which we propose the name *merrihueite* in honor of Craig M. Merrihue, of the Smithsonian Astrophysical Observatory, who died in March 1965.

Merrihueite occurs as inclusions in