16 July 1971, Volume 173, Number 3993 SCIENCE

Mariner Ultraviolet Spectrometer: Topography and Polar Cap

Ultraviolet measurements reveal the topography of Mars and show that ozone may be adsorbed on the polar cap.

Charles A. Barth and Charles W. Hord

Ultraviolet spectrum observations from the 1969 Mariner flyby missions yielded an unexpected abundance of meaningful data about the lower atmosphere and surface of Mars. The ultraviolet spectrometer experiment was designed primarily to determine the composition and structure of the Mars upper atmosphere (*1*). The experiment was successful in determining the properties of the lower atmosphere and surface because of two characteristics of the Mars surface. First, the ultraviolet reflectivity of the Mars surface in the desert region is low; and, second, the reflectivity of the polar cap in the ultraviolet is high. The first property means that any ultraviolet light reflected by the planet over desert regions is the result of scattering by atmospheric constituents; thus, ultraviolet intensity is a measure of the number of atmospheric scatterers. By interpretation of these measurements, the local atmospheric pressure may be determined; and variations in the local atmospheric pressure may be used to measure the topography of the planet. The second property (the high reflectivity of the polar cap) indicates that any ultraviolet absorber that lies on or above the polar cap may be detected by measuring the reflected ultraviolet light. An ultraviolet absorber, ozone, is present on the polar cap, and its presence may be indicative of a general property of a carbon dioxide polar cap—namely, the ability to adsorb minor constituents out of the atmosphere.

The authors are with the department of astrogeophysics and the Laboratory for Atmospheric and Space Physics of the University of Colorado, Boulder 80302.

Instrument and Spacecraft

The ultraviolet spectrometer, along with the television cameras and infrared instruments on the scan platform of the spacecraft, was aimed at selected regions of the planet as the two Mariners flew by Mars at 7 kilometers per second. Mariner 6 viewed several light and dark areas in the equatorial region; Mariner 7 flew farther south and obtained observations of the south polar cap and the bright desert region Hellas.

The field of view of the ultraviolet spectrometer through its 250-millimeter focal length telescope is 0.23 × 2.3 degrees. When the spacecraft was closest to the planet, the instrument viewed an area on the surface that was 10 by 100 kilometers. A spectral scan was completed every 3 seconds, during which time the projected field of view moved 21 kilometers in the direction of its narrow dimension. Although the spectral range of the 250-millimeter focal length scanning spectrometer is from 1100 to 4300 angstroms, the results reported here were obtained in the wavelength region between 2100 and 3600 angstrom at a resolution of 20 angstroms (*1*).

Disk Spectra

Several hundred spectra were obtained with the ultraviolet spectrometers pointed at various locations on the disk of Mars. Lighting conditions at the points of observation varied from the sun nearly overhead to near the horizon. These measurements were made at phase angles of 46, 63, and 90 degrees.

Three examples of the spectra observed over desert regions are shown in Fig. 1, where each spectrum is the sum of several individual spectra. The upper spectrum from the Candor region is an example of an observation made with a nearly overhead sun. The middle spectrum, which has the angles of incidence and emission nearly equal, was recorded near the western edge of Meridiani Sinus, where the radio occultation experiment measured the surface pressure (*2*). The lower spectrum was obtained in Deucalionis Regio, which was near the terminator during this observation.

Ultraviolet Reflectance

An example of the reflectance of the disk of Mars is shown in Fig. 2, which was obtained by dividing the spectrum from the Meridiani Sinus region by the spectrum of the sun that was measured in rocket experiments by the Naval Research Laboratory (*3*). The bulk of variation has been removed, and thus all the detail in the disk spectra can be seen to be due to the Fraunhofer structure in the solar spectrum. In fact, the variation that remains may be caused by an inexact comparison between the Mars spectra and the solar spectrum, which were obtained by two different techniques with different types of instrumentation. The reflectance of the Mars disk in the Meridiani Sinus region increases with decreasing wavelength. The monotonic increase in the reflectance at the shorter wavelengths is suggestive of atmospheric scatterers with an optical depth of $\tau = 0.1$ at 3050 angstroms. The same spectrum shape is found in most of the several hundred

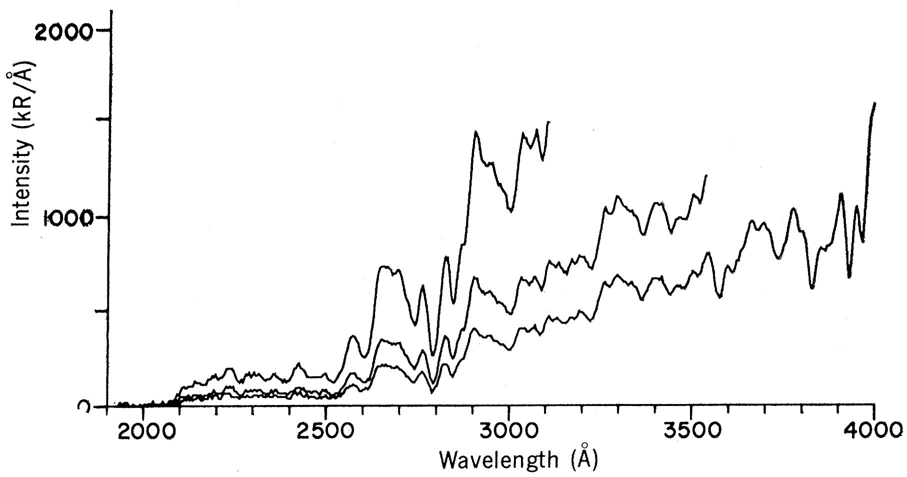

Fig. 1. Mars spectra observed over desert regions. The upper spectrum was obtained while the ultraviolet spectrometer was observing Mars at 4°N,70°W, with a solar zenith angle θ_0 of 20°, an emission zenith angle θ of 82°, and a phase angle ϕ of 63°. The middle spectrum was obtained at 1°S,9°W, with $\theta_0 = 47°$, $\theta = 42°$, and $\phi = 62°$. The lower spectrum was obtained at 18°S,350°W, with $\theta_0 = 65°$, $\theta = 27°$, and $\phi = 90°$.

ultraviolet spectra taken over the Mars desert regions. There is no evidence of ozone, which absorbs strongly between 2000 and 3000 angstroms, in any of the spectra obtained over the desert regions of Mars.

The magnitude of the reflectance attributed to atmospheric scattering is about three times that expected from a Rayleigh scattering atmosphere of pure carbon dioxide with a surface pressure of 6.6 millibars (*2*). Excess scattering is also observed in Earth's atmosphere, where it is attributed to the existence of aerosols. Results from both the Mariner television and Mariner infrared spectrometer indicated the existence of potential nonmolecular scatterers. The television experiments (*4*) showed a limb haze at altitudes between 15 and 40 kilometers, and the infrared spectrometer (*5*) measured a spectral reflection feature attributed to condensate of atmospheric carbon dioxide at the bright limb. The infrared spectrometer also observed an atmospheric spectrum feature at the dark limb, which is attributed to a silicate material. The particulate matter measured by these experiments may or may not be the same material that is producing the ultraviolet scattering.

Surface Pressure

If the ultraviolet reflectance of the desert regions of Mars is identified as originating primarily from atmospheric scattering, it becomes possible to determine the atmospheric pressure at the surface from the ultraviolet measurements (*6*). The method requires the assumption that small particles also contribute to the atmospheric scattering and that these particles are uniformly distributed in the atmosphere. This may or may not be a valid assumption. However, if the particles are small enough to produce the observed increased reflectivity with decreasing wavelengh, they would remain suspended in the atmosphere for very long times (*7*). Since the spectroscopic character of the data shows that the ground is essentially black in the ultraviolet and since the magnitude of the intensity shows that the scattering is optically thin, the ultraviolet reflectance should be directly proportional to the number of scatterers observed by the instrument. Since we have assumed that the total number of scatterers is proportional to the number of molecules and since the total number of molecules in a column is directly proportional to the pressure when the viewing geometry is taken into account, we may normalize the intensity to the pressure at one location and expect the ultraviolet intensity measured elsewhere along the observation track to be a direct measure of pressure.

The normalization point chosen was

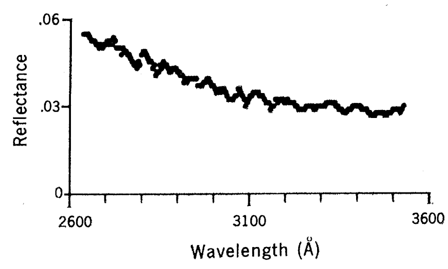

Fig. 2. Ultraviolet reflectance of a desert region. This reflectance was derived from the middle spectrum in Fig. 1.

centered at latitude 1°S and longitude 10°W near the Meridiani Sinus region, where the radio occultation experiment measured the surface pressure as 6.6 millibars (*2*). When this method was applied to the ultraviolet reflectance at 3050 angstroms, the surface pressure was found to vary along the observation track, with the lowest pressure being slightly greater than 4 millibars and the highest, 8 millibars.

Topography

When the variation of surface pressure along the observation track is compared with the surface features revealed by the television pictures from the Mariner spacecraft (*4*), there is a correlation between pressure variations and topographical features on both a small and a large scale. The most plausible explanation of this correlation is that the variation in the measured pressure is produced by elevation differences on the surface of Mars. The atmospheric pressure over high elevations is low, and the highest pressures are over the lowest elevations. A simple atmospheric model, in which the scale height near the surface is constant both as a function of altitude and location, was used to convert the pressure variations into altitude variations. A scale height of 10 kilometers was used, which is representative of the value measured by the radio occultation experiment at the Mariner 6 entry point (*2*). The elevation variation found from the Mariner observations has a total excursion of 7 kilometers, with the 8-millibar pressure corresponding to an elevation that is 3 kilometers lower than the Meridiani Sinus region, and the 4-millibar pressure to an elevation that is almost 4-kilometers higher than this reference level.

A detailed comparison between the elevation measurements and the topographic features is shown in Fig. 3. A map prepared by the Army Topographic Service shows, in addition to the classical names and markings, topographic detail derived from the Mariner 6 and Mariner 7 television pictures. The observation track of the ultraviolet spectrometer, shown by elongated areas enclosed by heavy lines, for the most part falls within the areas where near-encounter television pictures were obtained. These are shown in the rectangular areas enclosed by light lines. To facilitate comparison with the map, longitude is used as the parameter for the altitude data given in the lower part of the figure. The uppermost of the three graphs corresponds to the Mariner 6 track at the most northerly latitudes; the middle graph corresponds to the Mariner 6 track at middle latitudes; and the lowermost graph corresponds to the Mariner 7 tracks at the most southerly latitudes.

Detailed correlations may be recognized. Begin with the Mariner 6 track at 0°,70°W; the elevation starts high, drops rapidly in moving to the right, and then rises abruptly at 60°W. At this location, the map shows what appears to be a high crater wall being illuminated from the left. To the right, the elevation continues to fall and reaches a minimum at the edge of a crater wall at 48°W. The uppermost track at latitudes between 13°N and 2°S is more or less level on a large scale, but shows details that may be matched with individual craters. At 22°W, for example, a crater shows as a depression on the altitude scale. On the Mariner 6 track between 10° and 20°S, there is a general depression (when viewed from left to right) which reaches a minimum near 18°W and then rises farther to the right. The altitude variation from 43° to 18°W is 4 kilometers. The rise to the east from 18° to 350°W regains this 4 kilometers. Once again, there is a detailed correlation with individual craters—for example, at longitudes 11° and 13°W. The Mariner 7 track, which moves in a southeasterly direction starting at 35°S,50°W, shows a rapid rise of 4 kilometers, which reaches a peak at 44°S,41°W and then falls rapidly farther to the southeast. The large crater at 50°S,34°W shows up as a

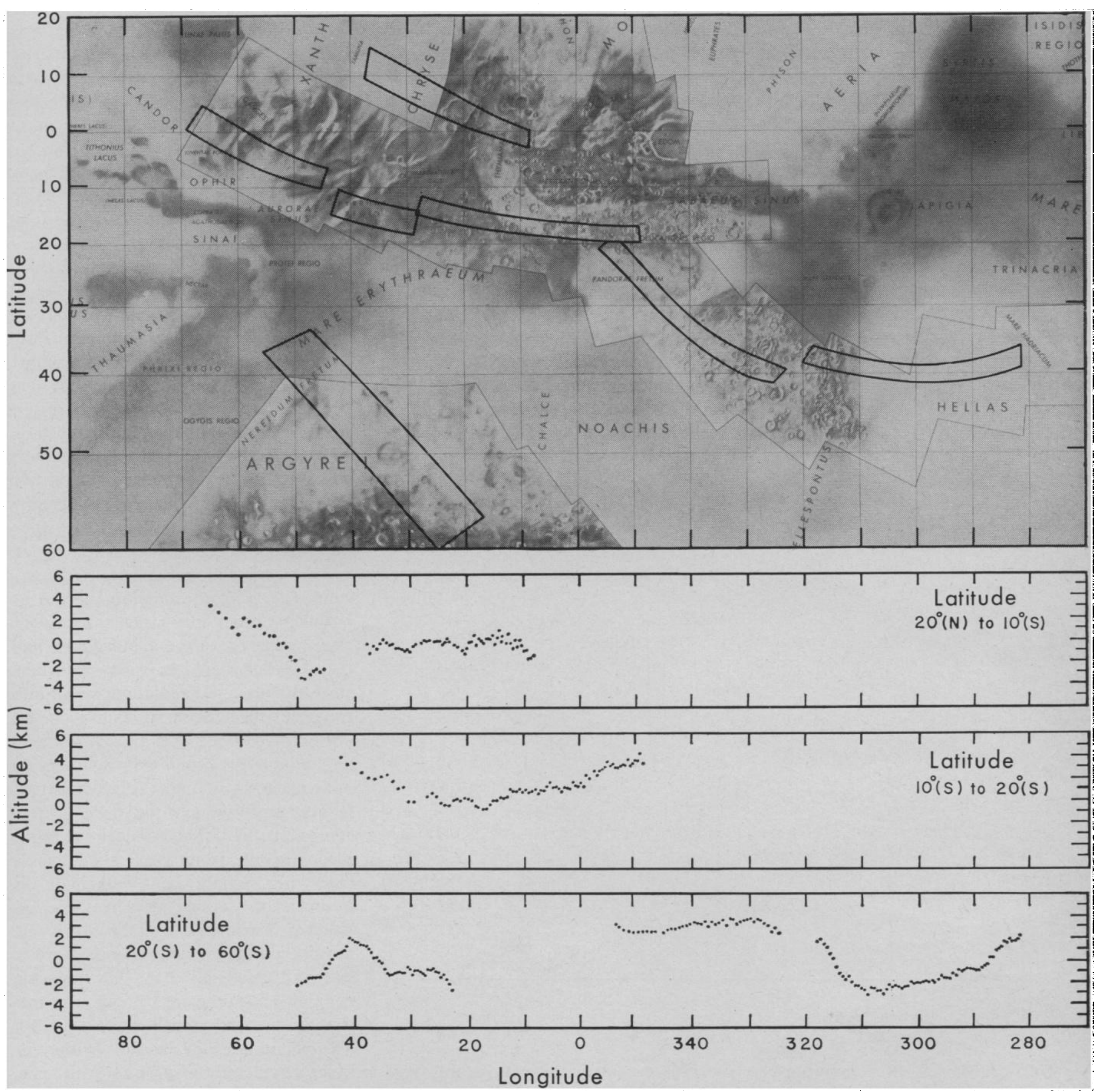

Fig. 3. Elevations of regions on Mars observed from Mariner 6 and Mariner 7. The areas enclosed by heavy lines on the map show the areas observed by the ultraviolet spectrometer. The upper graph gives altitude corresponding to the Mariner 6 observation tracks between 20°N and 10°S. The middle graph corresponds to the Mariner 6 tracks between 10° and 20°S, and the lower graph corresponds to the Mariner 7 tracks between 20° and 60°S.

depression. Starting at 20°S,355°W, the Mariner 7 track shows the Noachis region to be a high plateau with individual crater depressions. At 318°W, the elevation drops abruptly eastward into Hellas, a drop 5 kilometers in a horizontal distance of 500 kilometers. Hellas, which is devoid of craters, rises slowly in elevation as the observation track moves eastward.

The topography of Mars has also been mapped in part by ground-based radar, ground-based infrared observations (*8*), and the infrared spectrometer on Mariner 6 and Mariner 7 (*9*). Where it has been possible to compare the topography determined by the ultraviolet spectrometer, there is qualitative agreement. When the infrared and ultraviolet spectrometers viewed the same areas on Mars, the overall agreement was quantitative. Comparison on a detailed level reveals small-scale differences, notably in Hellas, where the ultraviolet measurements indicate a relatively smooth surface as compared with large variations in altitude observed by the infrared spectrometer. However, the overall agreement is strong circumstantial evidence that the basic concepts used in the two methods are correct.

Polar Cap

A series of ultraviolet spectrum observations were made across the southern desert regions and onto the polar cap at 60°S. The striking difference between the ultraviolet spectra of the desert regions and the polar cap is illustrated in Fig. 4. The lower spectrum was obtained over the Mare Australe region (55°S, 27°W), just north of the edge of the polar cap, and the upper spectrum was recorded well onto the polar cap at 65°S, 316°W. The polar cap spectrum is much more intense, a factor of 3 at 2900 angstroms; however, it falls off more rapidly toward shorter wavelengths; the ratio is about 2 at 2550 angstroms. In the polar cap spectra, as in the rest of the disk spectra, all of the spectrum detail that appears with 20-angstrom resolution is due to Fraunhofer features in the solar spectrum. Both the polar cap and desert spectra extend shortward to 2085 angstroms, where the incident solar spectrum has a discontinuity that drops sharply in intensity at shorter wavelengths.

The ultraviolet reflectance of the polar cap in the 2200- to 2900-angstrom wavelength region was obtained by dividing the Mars spectrum by the solar spectrum. Many spectrum fluctuations remain in the reflectance obtained by this method caused by the shortcomings of the available solar spectrum shortward of 2635 angstroms. A better method to determine the spectrum characteristics of the polar cap is to divide the polar cap spectrum by a desert spectrum obtained at similar lighting angles. The resulting ratio (plotted in Fig. 5) shows a broad absorption feature centered at 2550 angstroms. The prime candidate to explain this absorption is ozone, which has an absorption continuum between 2000 and 3000 angstroms, centered at 2550 angstroms. Each of the 45 polar cap spectra has the spectrum absorption shape expected from ozone. Ozone is likely to be produced in the photochemistry of a carbon dioxide atmosphere (*10*).

Where might this absorber be located to produce the characteristics that appear in the polar cap spectra? First, the observed absorption could be a property of the polar cap itself; second, the absorber could be in the atmosphere above the polar cap but not over the rest of the planet; and, third, the absorber could exist in the atmosphere over the entire planet but only be seen when viewed with the bright cap as background. We will consider the third possibility first: for a planet-wide absorber to be visible only over the polar cap, it must have a small scale height. Over the desert regions, where the ground albedo is very small, the absorber would go undetected because it would lie beneath the bulk of the atmospheric scatterers. Over the polar cap, where the ground albedo is high, the absorber would be easily detectable since the observed radiation would have traversed the absorbing layer twice.

If the absorber is in the atmosphere, an amount of ozone equivalent to an optical depth of 0.3 at 2550 angstroms is needed to match the data. This is equivalent to 1×10^{-3} centimeter-atmosphere of ozone or 3×10^{16} molecules per square centimeter. If this number of ozone molecules is distributed uniformly in the lower atmosphere, the volume density at the surface would be 3×10^{10} molecules per cubic centimeter, or a mixing ratio slightly greater than one part in 10^7. This amount of ozone falls within the range calculated by carbon dioxide photochemistry (*10*). A solution to the mystery of why the desert spectra do not show the ozone absorption has been suggested by Sagan (*11*). There may be

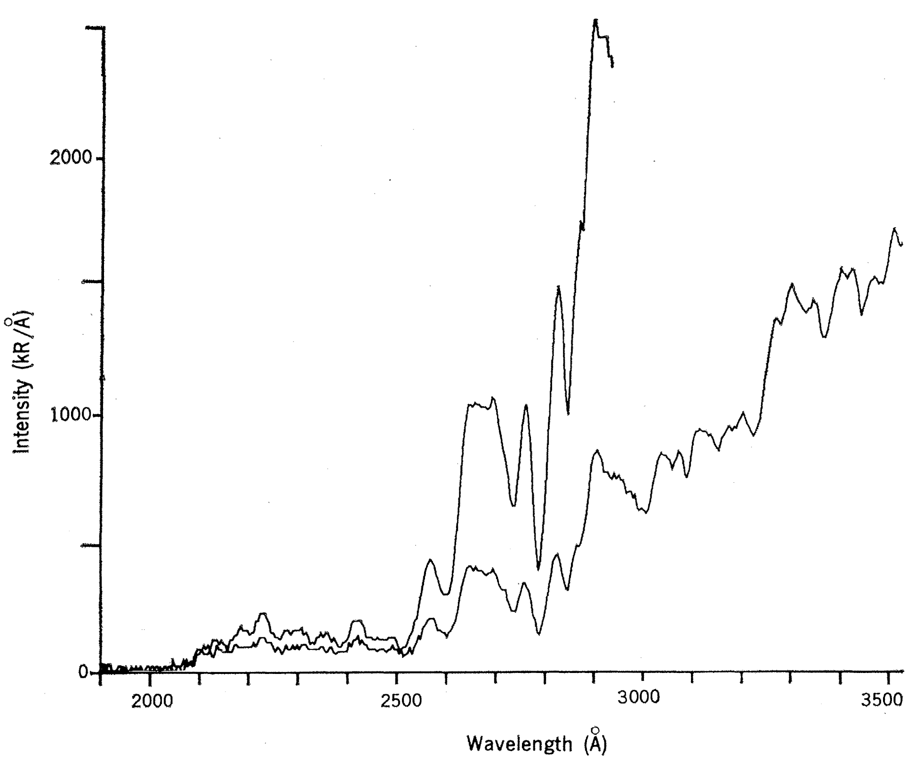

Fig. 4. Comparison of Mars spectrum observed over the polar cap with one observed over desert region. The upper spectrum was obtained while the ultraviolet spectrometer was observing the polar cap at 67°S,5°W, with a solar zenith angle θ_0 of 41°, an emission zenith angle θ of 58°, and a phase angle of 55°. The lower spectrum was obtained while the spectrometer was observing the desert at 54°S,29°W, with $\theta_0 = 51°$, $\theta = 50°$, and $\phi = 55°$.

more particulate aerosols above the deserts than above the polar caps. The dust above the desert regions would shield the ozone from observation.

An ingenious hypothesis suggested by Broida is that the ozone is trapped in the solid carbon dioxide of the polar cap and the observed spectrum is that of the trapped ozone. Laboratory measurements show that the reflectance of freshly precipitated solid carbon dioxide is large and constant with wavelength between 2000 and 3000 angstroms. Broida and his collaborators (*12*) have shown that solid carbon dioxide with ozone trapped in it shows the ultraviolet absorption that is characteristic of ozone. These same laboratory experiments have also shown that ozone is adsorbed when it is brought in contact with solid carbon dioxide. This result suggests that the carbon dioxide polar cap on Mars serves as a sink for nonvolatile gases, as well as for the volatiles that condense out at the temperature of the cap. Gases such as oxygen, methane, and ammonia, if they are present in the Mars atmosphere at all, may be adsorbed or trapped on the polar cap along with the water that will condense there. When the cap sublimes, the trapped gases including ozone would be released and would produce a local source in the atmosphere.

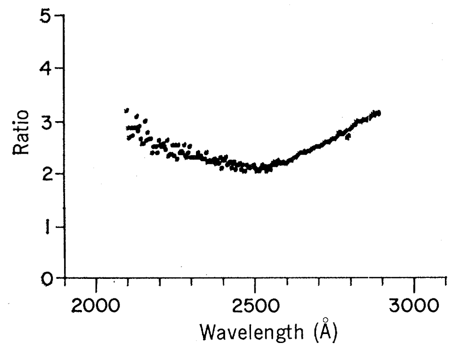

Fig. 5. Ratio of reflectance of polar cap to reflectance of a desert region. This ratio was obtained by dividing the upper spectrum of Fig. 4 by the middle spectrum of Fig. 1.

Landing Sites

In the fall of 1971, it is anticipated that a Mariner spacecraft will orbit Mars and, with its complement of scientific instruments, will make extensive observations over the entire planet. One of the instruments is an ultraviolet spectrometer, which will be able to carry out the topographical mapping over nearly all the desert regions and will also be able to study the behavior of ozone on the polar cap for an extended period (*6*). In addition to the intrinsic importance of these observations, they will aid directly in plans to select landing sites for unmanned spacecraft that are planned for future years.

There are several reasons why it may be desirable to land in a region of low elevation and high pressure (*13*). If the landing vehicle uses aerodynamic braking as part of the landing technique, such a system could be made simpler if it were designed to be operated where the pressure was 8 millibars rather than 4 millibars. If it is considered desirable to land in a region where there is the greatest probability of finding liquid water, then a low elevation is desirable. Water vapor has been measured in the Mars atmosphere from ground-based telescopes, but, because of the low atmospheric pressure, liquid water may not be present on the surface (*14*). Since one objective of a spacecraft landing on Mars may be to determine whether or not liquid water is present, the plausible place to search is at low elevations where the atmospheric pressure is greater than 6 millibars, the pressure corresponding to the triple point of water (*14*). The amount and form of the water retained by Mars are of interest in understanding the formation and evolution of the planet. Biological experiments are most likely to meet with early success if they are performed at a location where water is available in liquid form. The pressure mapping by the ultraviolet spectrometer experiment on the 1971 Mariner spacecraft should help locate such places on Mars.

Another criterion in selecting a landing site may be the desire to enhance the probability of detecting minor constituents in the lower atmosphere that might be present as the result of biological or geological activity. The interpretation of the ultraviolet spectrometer data that the polar cap adsorbs ozone suggests that the solid carbon dioxide cap might be an efficient trap for other gases as well. A landing site chosen within the polar cap boundary would allow analytical instrumentation on a Mars lander to take advantage of the concentrating effect of this adsorption trap. The chemical history of the previous season may be found there. During the 1971 Mariner experiments, the idea that the polar cap traps minor constituents may be verified and its temporal behavior determined.

Summary

Mars, the red planet, reflects sunlight in the ultraviolet, but it is the atmosphere, not the surface, that is responsible for the reflected light. Even though there are atmospheric scatterers in addition to the molecular scatterers, it is possible to relate the intensity of the scattered radiation with the atmospheric pressure. The variation of pressure over the planet reveals the topography to vary over 7 kilometers in height and to be correlated with visible features. The carbon dioxide polar cap, in addition to being a cold trap for volatile gases in the atmosphere, may also be a very efficient adsorption trap for nonvolatiles. This last property may make the cap a repository for gases produced by geological or biological activity (*15*).

References and Notes

1. C. A. Barth, *Appl. Opt.* **8**, 1295 (1969); ———, W. G. Fastie, C. W. Hord, J. B. Pearce, K. K. Kelly, A. I. Stewart, G. E. Thomas, G. P. Anderson, O. F. Raper, *Science* **165**, 1004 (1969); C. A. Barth, C. W. Hord, J. B. Pearce, K. K. Kelly, G. P. Anderson, A. I. Stewart, *J. Geophys. Res.* **76**, 2213 (1971); J. B. Pearce, K. A. Gause, E. F. Mackey, K. K. Kelly, W. G. Fastie, C. A. Barth, *Appl. Opt.* **10**, 805 (1971).
2. A. Kliore, G. Fjeldbo, B. L. Seidel, S. I. Rasool, *Science* **166**, 1393 (1969); S. I. Rasool, J. S. Hogan, R. W. Stewart, L. H. Russell, *J. Atmos. Sci.* **27**, 841 (1970).
3. N. Wilson, R. Tousey, J. D. Purcell, F. S. Johnson, C. E. Moore, *Astrophys. J.* **119**, 590 (1954); R. Tousey, *Space Sci. Rev.* **2**, 3 (1963).
4. R. B. Leighton, N. H. Horowitz, B. C. Murray, R. P. Sharp, A. H. Herriman, A. T. Young, B. A. Smith, M. E. Davies, C. B. Leovy, *Science* **166**, 49 (1969); C. B. Leovy, B. A. Smith, A. T. Young, R. B. Leighton, *J. Geophys. Res.* **76**, 297 (1971).
5. K. C. Herr and G. C. Pimentel, *Science* **167**, 47 (1970).
6. C. W. Hord, C. A. Barth, J. B. Pearce, *Icarus* **12**, 63 (1970).
7. J. B. Pollack and C. Sagan, *Space Sci. Rev.* **9**, 243 (1969).
8. G. H. Pettengill, C. C. Counselman, L. P. Rainville, I. I. Shapiro, *Astron. J.* **74**, 461 (1969); M. J. S. Belton and D. M. Hunten, *Science* **166**, 225 (1969).
9. K. C. Herr, D. Horn, J. M. McAfee, G. C. Pimentel, *Astron. J.* **75**, 883 (1970). The interpretation that the ultraviolet spectrometer was actually measuring topography received a strong impetus from the early publication of the topography results of the infrared spectrometer. When a comparison is made between the detailed results of the two experiments, the differences as well as the agreements between the two techniques should reveal still more information about the Mars lower atmosphere and surface.
10. M. B. McElroy and D. M. Hunten, *J. Geophys. Res.* **75**, 1188 (1970); D. M. Hunten and M. B. McElroy, *ibid.*, p. 5989.
11. C. Sagan, personal communication.
12. H. P. Broida, O. R. Lundell, H. I. Schiff, R. D. Ketcheson, *Science* **170**, 1402 (1970).
13. C. Sagan and J. B. Pollack, *J. Geophys. Res.* **73**, 1373 (1968).
14. T. Owen and H. P. Mason, *Science* **165**, 893 (1969); A. P. Ingersoll, *ibid.* **168**, 972 (1970); E. S. Barker, R. A. Schorn, A. Woszczyk, R. G. Tull, S. J. Little, *ibid.* **170**, 1308 (1970).
15. For some years now, the Stanford University biologist Joshua Lederberg has advocated a polar landing site for Viking.
16. This research was sponsored by the National Aeronautics and Space Administration.