ning horizontally across the picture. Two linear ridges are also seen: Kepler Dorsum, which was earlier seen by Mariner 9, is at the bottom, and a newly discovered ridge runs from the lower left to upper right. The large depression near the bottom is one of the regions viewed by Viking which indicates a smaller volume for Phobos than determined from Mariner 9 data. Hummocks and halo craters are also visible.

The top of Fig. 6 is a four-picture photomosaic taken at a range of 300 km as VO-1 approached Phobos. Three pictures (A through C), taken at a range of 110 km from the surface as VO-1 flew by Phobos, are shown at the bottom of Fig. 6. Surface areas covered by the three pictures are outlined on the photomosaic. The upper right area of the photomosaic shows the same region as in the upper left of Fig. 5, a region dominated by striations. Two large craters with dark material on their floors are seen near the bottom of the photomosaic. The three pictures show a heavily cratered surface; craters as small 10 to 15 m are visible.

The primary effort during the next few months will be devoted to refining the density estimate. This will involve processing radio data to determine the mass more accurately and processing imaging data to determine the volume more accurately. The volume estimate will most likely limit the accuracy of the density estimate. If the very low density of ~2 g/$cm^3$ holds up under more detailed analysis, one will be forced to conclude that Phobos is an object which originally formed in the asteroid belt or that Lewis's model of planetary condensation, which claims that type I carbonaceous chondrite material cannot form at Mars's distance from the sun, is incorrect (*6*).

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## The Composition of Phobos: Evidence for Carbonaceous Chondrite Surface from Spectral Analysis

Abstract. *A reflectance spectrum of Phobos (from 200 to 1100 nanometers) has been compiled from the Mariner 9 ultraviolet spectrometer, Viking lander imaging, and ground-based photometric data. The reflectance of the martian satellite is approximately constant at 5 percent from 1100 to 400 nanometers but drops sharply below 400 nanometers, reaching a value of 1 percent at 200 nanometers. The spectral albedo of Phobos bears a striking resemblance to that of asteroids (1) Ceres and (2) Pallas. Comparison of the reflectance spectra of asteroids with those of meteorites has shown that the spectral signature of Ceres is indicative of a carbonaceous chondritic composition. A physical explanation of how the compositional information is imposed on the reflectance spectrum is given. On the basis of a good match between the reflectance spectra of Phobos and Ceres and the extensive research that has been done to infer the composition of Ceres, it seems reasonable to believe that the surface composition of Phobos is similar to that of carbonaceous chondrites. This suggestion is consistent with the recently determined low density of Mars's inner satellite. Our result and recent Viking noble gas measurements suggest different modes of origin for Mars and Phobos.*

The composition of Phobos could be an important clue to understanding the origin of this martian satellite. Ground-based, Mariner 9, and Viking orbiter visible-wavelength photometric data have shown that the martian moons are very dark and gray in color. The low and neutral visual albedos are consistent with a surface consisting of either very dark basalts or carbonaceous chondrites, materials expected to be common in the solar system (*1–3*). The two possibilities still permit a wide latitude of possible origins. If the satellites are basaltic, then they are probably fragments of a much larger body or bodies since the formation of basalt, an igneous rock, requires melting and mineral differentiation in a parent body, and it is unlikely that such processes could take place in objects as small as the martian moons. On the other hand, a carbonaceous chondritic composition implies an ultraprimitive origin because such mineral mixtures are believed to have condensed directly from the primeval solar nebula (*4*). Therefore, in order to settle the question of the satellite's origin, we must have more definitive information on its composition. We have compiled an ultraviolet-visible-infrared reflectance spectrum of Phobos from the Mariner 9 ultraviolet spectrometer (UVS), Viking lander imaging, and ground-based photometric data, and have deduced its probable surface composition by comparing our spectrum with the spectra of asteroids of known composition.

Mariner 9 ultraviolet spectra of Phobos at a resolution of 1.5 nm were taken during the 48th and 80th revolutions of the spacecraft around Mars. A decalibrated spectrum and lower limits on Phobos's reflectance have been published elsewhere (*5*). Pang and Ajello have successfully used UVS data to infer the martian surface composition (*6*). During a satellite observing sequence, the spectrometer's field of view (FOV) was allowed to drift slowly across Phobos. Since our FOV is larger than the angular size of the illuminated disk, an observed light curve has a flat top. The brightest spectra from each observing sequence were averaged to improve the signal-to-noise ratio. Data were taken at phase angles of 49°, 50°, and 83°.

We obtained the phase coefficient of Phobos after correcting for changing Mars-sun and satellite-spacecraft distances as well as nonsphericity effects, following the procedure in (*7*). The ultraviolet phase coefficient is 0.032 ± 0.005 per degree, similar to that at visible wavelengths (*7*). Extrapolating our phase curve to a phase angle of 0° gave Phobos's brightness at opposition without the "opposition effect." We decalibrated the spectrum and corrected for the underfilling of our FOV. We then obtained Phobos's spectral geometric albedo by dividing this spectrum by a standard solar spectrum (*8*) appropriate for the Mars-sun distance. Ultraviolet geometric albedos at 10-nm band centers are plotted as upright triangles in Fig. 1.

Absolute calibration of the Mariner 9 UVS was carried out before flight with a standard tungsten lamp down to 225 nm and a National Bureau of Standards photodiode at shorter wavelengths. The molecular branching ratio technique of relative calibration was used to check the absolute calibration. Bohlin *et al.* (*9*) have verified the calibration by making a rocket-borne observation of standard stars, using a replica. The calibration was maintained by periodic observations of standard stars after Mars orbit insertion. The absolute stellar energy distributions derived from Mariner 9 UVS data were compared with those found by rocket-borne and Orbiting Astronomical Observatory-2 (OAO-2) ultraviolet spectrometers and predicted by models of the stellar atmosphere. All observations agree with one another to within the accuracy of their absolute calibrations (±20 to 30 percent) (*10*). Both laboratory and in-flight calibrations show the absolute uncertainty of the UVS measurements to be about ±20 percent, with a relative uncertainty of about ±7 percent. The relative uncertainty is shown in Fig. 1 as a sample error bar.

Viking lander imaging data, discussed by Pollack *et al.* (*11*), are shown as inverted triangles in Fig. 1. The Viking data have an absolute accuracy of ±20 percent and a relative accuracy (error bars) of ±5 percent. Zellner and Capen (*1*) made photoelectric observations of Phobos and derived a visual (V) geometric albedo of 0.059 for the satellite. Zellner (*12*) has since informed us that the correction of these Phobos measurements to a phase angle of 0° had been improperly done. Rectifying an inadvertent sign error on their part, we arrived at an opposition V magnitude and geometric albedo of 12.1 and 0.050, respectively. Using the new V magnitude and Kuiper's blue-visual (B-V) color index (*1*), we found a blue geometric albedo of 0.051. The ground-based data are plotted as closed squares in Fig. 1. An uncertainty of ±0.2 in the magnitudes has been converted into the error bars shown. The average of the three Viking and two ground-based values is 0.049, which is close to the value of 0.050 derived from Viking lander survey-mode (broadband, 400 to 1100 nm) imaging data (*11*).

The combined Mariner 9, Viking, and ground-based data show that the reflectivity of Phobos is flat from 1100 to 400 nm but decreases sharply in the ultraviolet to about 1 percent at 212 nm. The reflectance spectrum of Phobos is quite different from that of the moon (*13*) (Fig. 1) but is similar to those of asteroids (1) Ceres and (2) Pallas. We obtained the open squares (Fig. 1) by normalizing relative multispectral observations (*14*) to the adopted visual geometric albedo of Ceres, 0.054 (*15*). The OAO-2 broadband photometric data of Ceres (circles) and Pallas (crosses) in ultraviolet light (*16*) (Fig. 1) have relative uncertainties of ±0.001 to ±0.006. Ground-based observations of Pallas give essentially constant visible-infrared albedos, although its absolute V albedo is somewhat higher than that of Ceres (*15*). The long-wavelength values of Pallas are not shown. There is no normalization between the different sets of data in Fig. 1.

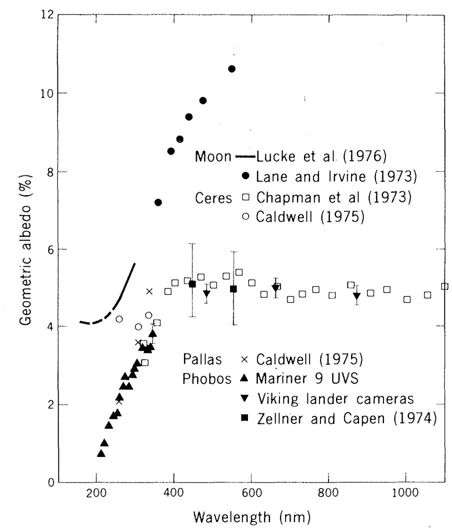


Fig. 1. The spectral albedo of the moon, asteroids (1) Ceres and (2) Pallas, and the martian satellite Phobos. There is no normalization between the different sets of data in this figure.

A great deal of work has been done to infer the surface composition of asteroids by matching their reflectance spectra with those of meteorites (*17*). Independent spectrophotometric observations from 0.3 to 2.2 μm have shown that Ceres and Pallas have surface compositions similar to that of carbonaceous chondrites (*18, 19*). On the basis of a review of all available spectrophotometric observations of asteroids and laboratory spectra of meteorites, Chapman *et al.* (*17*) reaffirmed this finding.

Even if the reflectance spectrum of asteroid X resembles that of meteorite Y, does it necessarily follow that X has a surface composition similar to Y? A similarity in reflectance spectra is almost certainly a necessary condition for the similarity of the composition of an asteroidal surface and a meteorite, but is it a sufficient condition? Recent research into the physical phenomena which relate the chemical composition of mineral assemblages to their reflectance spectra provide reason for confidence that this is so (*20*). We will make use of the general principles established in extensive lunar and asteroidal remote-sensing and give a physical explanation for the spectral signature common to carbonaceous chondrites in what follows. Much chemical and dynamic evidence also suggests a genetic relationship between meteoritic and asteroidal materials.

The low and flat visible-infrared reflectance of carbonaceous materials can be easily explained. Johnson and Fanale (*19*) found that only 5 percent carbon black masks all the strong infrared bands of montmorillonite, a major constituent of type 1 carbonaceous chondrites. In such a mixture, absorption by the opaque phase dominates light transfer within the medium so that the "body colors" of the main phase do not show up. The imaginary index ($k$) of carbon has values between 0.1 and 1 (*21*); thus all visible and near-infrared bands of the silicate phase are quenched, because the $k$ of silicates does not exceed 0.01 until wavelengths longer than 5 μm (*22*).

Johnson and Fanale (*19*) found that the ultraviolet-blue reflectance slope of montmorillonite is not masked by the opaques, and it shows up as an ultraviolet drop-off in the composite spectrum. This phenomenon may be explained as follows: as the imaginary index of silicates approaches and finally exceeds 0.01 at the short wavelengths (*22*), little or none of the light incident on the surface is transmitted to below a depth of micrometers. In this limit, it is the relative abundance of the phases on the surface that determines the reflectance spectrum—the "checkerboard effect." Since the abundance of the silicates greatly exceeds that of the opaques, the silicates are expected to contribute most to the "surface colors." Consequently, it is in the ultraviolet and middle-infrared region that we find the spectral signatures of the main phase when it is mixed with several percent or more opaques.

On the basis of a good match between the reflectance spectra of Phobos and Ceres, and taking advantage of the extensive research done to identify the surface composition of this asteroid, we conclude that the surface composition of Phobos is also similar to that of carbonaceous chondrites. This identification is not unique, as one can probably find materials other than carbonaceous chondrites that have a spectral signature similar to that of Phobos. However, the cosmic abundance of silicates and carbon strongly supports carbonaceous chondrites as the most likely candidates.

The observed surface composition should be representative of the composition to a depth of at least hundreds of meters. Cratering studies have shown that a large volume of material on

Phobos has been excavated and fragmented by impacts. The mean excavation depth was estimated to be hundreds of meters (*2*). Material ejected from Phobos has remained in the gravitational potential well of Mars, and a significant fraction was later recaptured to form a regolith on the satellite (*23*). The fact that Phobos shows neither albedo nor color variation down to a resolution of 200 m (*3*) supports this conclusion. If material in the interior were excavated and then darkened by exogenous processes similar to those on Earth's moon, we would see bright (fresh) and dark (old) features like the rays on the lunar surface (*24*).

Is the surface composition of Phobos, Ceres, or any other carbonaceous body really the same as the bulk composition? Is it possible that the carbonaceous material is merely a superficial deposit, perhaps accreted from meteoritic or cometary debris? Morrison (*25*) reviewed the size and density of Ceres and concluded that the low density of this asteroid ($\sim 2.5$ g/cm$^3$) is consistent with a bulk composition similar to that of carbonaceous chondrites. Laboratory photometric studies of returned lunar samples show no evidence that the meteoritic component controls the bulk spectral reflectivity (*26*).

Our identification of a carbonaceous chondritic composition for Phobos is consistent with the implications of a recent mass estimate for the satellite based on the perturbations on the orbit of Viking 1 by Phobos, during a series of close encounters. This mass estimate yields a density of $2.0 \pm 0.6$ g/cm$^3$ (*27*). Such a low density is consistent with that of type 1 or type 2 carbonaceous chondrites, but it definitely rules out basalts which have densities close to 3 g/cm$^3$. Our reflectance data and the low-density value have eliminated the possibility that Phobos originated from a parent body large enough to have melted and differentiated to form basalts. Rasool and Le Sergeant (*28*) found that the relative abundance and total amounts of noble gases on Mars, measured by Viking, can best be explained if the outer layers of Mars were made of material similar to that of ordinary chondrites (type LL) as suggested by Anders (*29*) rather than carbonaceous chondrites as assumed by a number of investigators in recent years. Both our work and (*28*) point to different modes of origin for Mars and Phobos.

In order to choose among other possible origins, we must determine precisely which type of carbonaceous chondrite material Phobos most resembles.

If Phobos is made of the most primitive type carbonaceous chondrite material (C1), as its low density suggests, then the satellite is almost certainly a captured body which formed in the asteroid belt, since volatile-rich C1 materials probably did not form as close to the sun as Mars (*30*). The uncertainty in the density value still allows the possibility that Phobos is made of C2 carbonaceous chondrite material, as C2 materials have densities in the range 2.5 to 2.9 g/cm$^3$ (*31*); C2 material has volatile contents between those of C1 and C3 materials. Type 1 carbonaceous chondrites contain no chondrules but are so classed because they are chemically and mineralogically similar to the chondrule-bearing stones of the same type; type 2 carbonaceous chondrites contain chondrules. Practically all investigators have accepted the idea that chondrules were once molten drops. This hypothesis requires a high temperature and a liquid state of the meteoritic material at one stage of its development. Consequently, a high-temperature origin with some dehydration and reduction but not differentiation still remains a possible interpretation. Refined analyses of our spectral data for secondary features may enable us to test the possibility that Phobos is indeed made of C1 material.

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## Multicolor Observations of Phobos with the Viking Lander Cameras: Evidence for a Carbonaceous Chondritic Composition

Abstract. *The reflectivity of Phobos has been determined in the spectral region from 0.4 to 1.1 micrometers from images taken with a Viking lander camera. The reflectivity curve is flat in this spectral interval and the geometric albedo equals 0.05 ± 0.01. These results, together with Phobos's reflectivity spectrum in the ultraviolet, are compared with laboratory spectra of carbonaceous chondrites and basalts. The spectra of carbonaceous chondrites are consistent with the observations, whereas the basalt spectra are not. These findings raise the possibility that Phobos may be a captured object rather than a natural satellite of Mars.*

Phobos, the inner moon of Mars, might have been created as part of the same event that gave birth to Mars or it may have formed elsewhere and subsequently been captured by Mars. The satellite's orbital characteristics provide some constraints upon hypotheses of its origin and early history (*1*). Additional clues may be provided by its composition.