Reports

Viking First Encounter of Phobos: Preliminary Results

Abstract. *During the last 2 weeks of February 1977, an intensive scientific investigation of the martian satellite Phobos was conducted by the Viking Orbiter-1 (VO-1) spacecraft. More than 125 television pictures were obtained during this period and infrared observations were made. About 80 percent of the illuminated hemisphere was imaged at a resolution of about 30 meters. Higher resolution images of limited areas were also obtained. Flyby distances within 80 kilometers of the surface were achieved. An estimate of the mass of Phobos* (GM) *was obtained by observing the effect of Phobos's gravity on the orbit of VO-1 as sensed by Earth-based radiometric tracking. Preliminary results indicate a value of* GM *of 0.00066 ± 0.00012 cubic kilometer per second squared (standard deviation of 3) and a mean density of about 1.9 ± 0.6 gram per cubic centimeter (standard deviation of 3). This low density, together with the low albedo and the recently determined spectral reflectance, suggest that Phobos is compositionally similar to type I carbonaceous chondrites. Thus, either this object formed in the outer part of the asteroid belt or Lewis's theory that such material cannot condense at 1.5 astronomical units is incorrect. The data on Phobos obtained during this first encounter period are comparable in quantity to all of the data on Mars returned by Mariner flights 4, 6, and 7.*

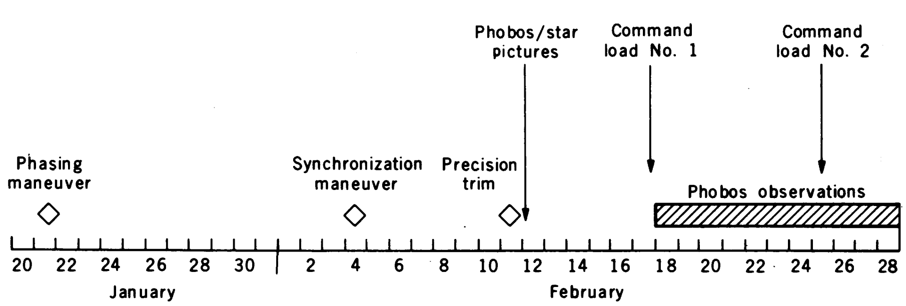
Experiment design studies (*1*) showed that close flybys of the martian satellites Phobos and Deimos could be obtained with only small changes in the orbits of the two Viking spacecraft. Encounter opportunities exist when the spacecraft orbit nearly intersects the satellite's orbit. A small phasing maneuver is used to guarantee that the spacecraft and satellite are near the intersection point of the orbits at about the same time. The orbital period of the spacecraft can also be designed to be an integral multiple of the orbital period of the satellite (for example, 3/1 for Phobos and 5/4 for Deimos) to give many close encounters. However, the rotation of the spacecraft orbit's line of apsides limits the close encounter periods to a few weeks.

The opportunities for these close satellite encounters occur throughout the Viking extended mission. Viking Orbiter-1 (VO-1) made a series of close flybys of Phobos in February and May 1977, and there is an opportunity for a close flyby of Deimos in October 1977. Viking Orbiter-2 also has a close flyby opportunity of Deimos in October 1977. A special team, including members of the radio science, orbiter imaging, and infrared thermal mapping teams, was formed to take advantage of these close encounters. The primary objectives of the team were to: (i) determine satellite masses to 10 percent, (ii) determine the satellite volumes to 10 percent, (iii) obtain high-resolution (10 to 20 m) imaging of the surfaces, and (iv) obtain high-resolution (1 to 2 km) infrared coverage of the satellites.

These data should yield satellite densities to about 10 percent, an accuracy sufficient to permit differentiation between a primitive carbonaceous chondrite and a basalt composition. The high-resolution surface coverage is valuable for analyzing the regolith and the crater morphology on a body of very small gravitational attraction.

The Phobos encounter series in February 1977 has been successfully completed. A series of three maneuvers carried out in late January and early February (Fig. 1) was used to phase the passage of VO-1 through the orbit intersection point with the passage of Phobos. Also the orbital period of VO-1 was changed to approximately 23 hours, resulting in a 3/1 commensurability with the orbital period of Phobos. The last maneuver was a precision trim to properly target the closest of the flybys which occurred on 20 February 1977. Directly after the final precision trim maneuver, ten pictures of Phobos and stars (Fig. 2) were taken to tie the encounter trajectory of VO-1 directly to Phobos's orbit for final encounter sequence planning. Commands were transmitted to the VO-1 computer on 18 February and 25 February to control all spacecraft activities during the 10-day encounter period.

The flyby geometries for the encounter period are shown in Fig. 3. Phobos is shown as seen from an approaching spacecraft in a coordinate system with the T axis parallel to the Mars equatorial plane. The direction to the sun is about 16° above T and 37° into the plane of the paper, whereas Mars is 63° below T and



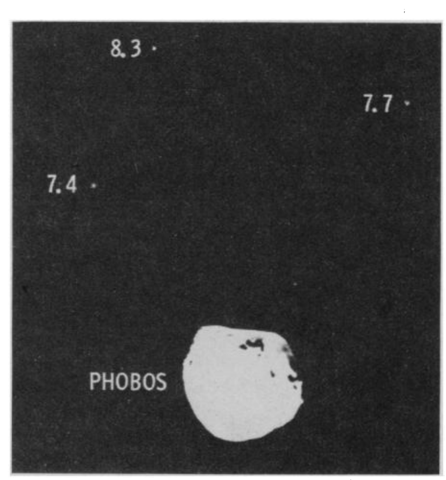


Fig. 1 (left). Three trajectory correction maneuvers were performed in late January and early February 1977 to target the VO-1 spacecraft encounter of Phobos. Directly after the third maneuver, pictures of Phobos against a star background (Fig. 2) were taken to determine the position of Phobos relative to the encounter spacecraft orbit. Commands to execute the science data sequences taken during the 10-day observation period were transmitted at the beginning and middle of the observation period. However, because of the complexities of the encounter, commands were actually transmitted on a daily basis for the first 5 days. Fig. 2 (right). Phobos is seen with three stars ranging in visual magnitude from 7.4 to 8.3. This picture (235A01) was the first in a series of ten pictures taken directly after the final precision trim maneuver. The image of Phobos is saturated and smeared because of the long exposure used for the stars. The pictures were used to determine the orbit of Phobos relative to the orbit of VO-1. The orbit of VO-1 relative to Mars was determined from Earth-based radio data. Accurate position predictions of Phobos relative to VO-1 were needed to calculate science instrument pointing during the close encounters.

50° out of the plane of the paper. The dots above and to the right of Phobos indicate the points of closest flyby for each passage during the encounter period. The positional behavior of the dots reflects the secular effect of apsidal rate and the perturbations of the martian gravity field and the mass of Phobos on the spacecraft. The trajectory design gave flybys on the illuminated side of Phobos within 80 to 300 km during the entire encounter period.

The primary encounter observations of Phobos included visual and infrared imaging as well as radio tracking of VO-1 while it was under the gravitational influence of Phobos. The visual imaging was obtained from two narrow-angle television cameras (*2*), and the infrared observations were obtained from an infrared thermal mapper. Radio data included S- and X-band Doppler and ranging data to VO-1 with a 10-second Doppler count during a 30-minute period centered around each flyby.

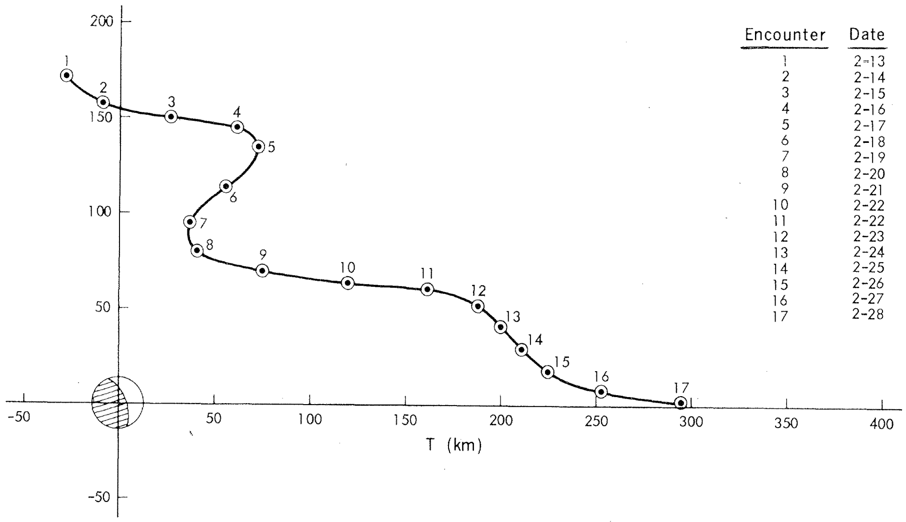


Fig. 3. The distance of VO-1 to Phobos is shown for each flyby (one flyby per ~23 hours). The view is as would be seen as VO-1 approached Phobos with the *T* axis parallel to the martian equatorial plane. A closest flyby distance of 88 km was achieved on 20 February 1977. All flybys were within 300 km during this 2-week encounter period.

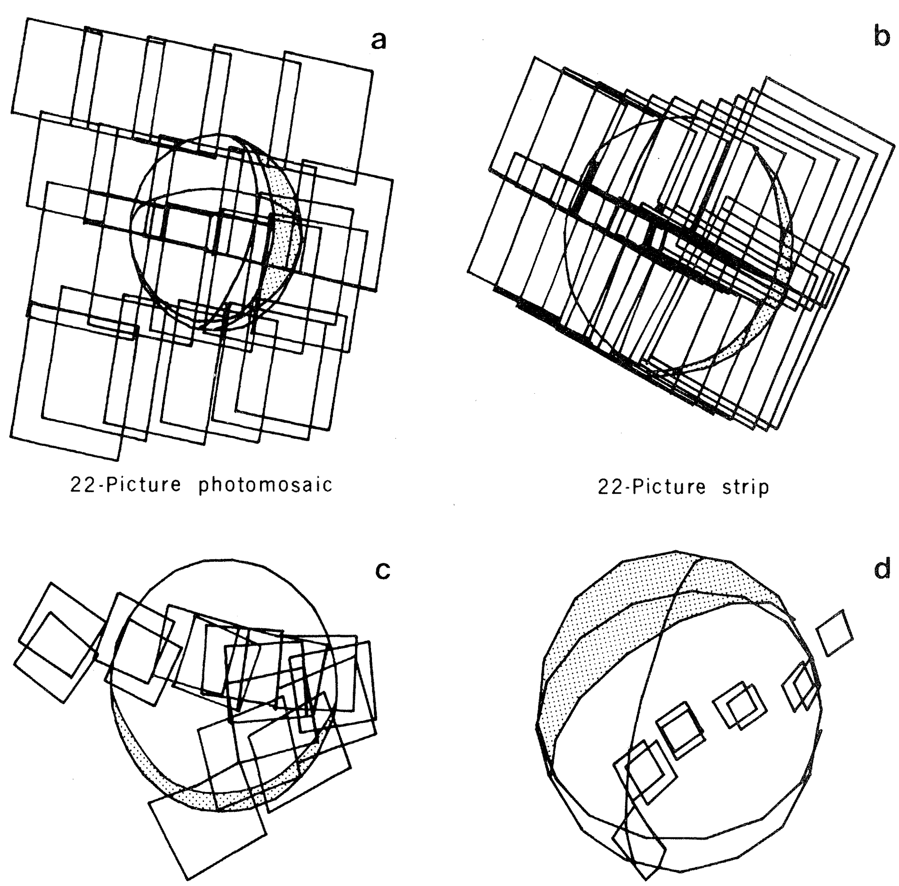


Fig. 4. Four basic television picture sequences were used to image Phobos near encounter: (a) and (b) were taken at range greater than 400 km to completely cover Phobos; (c) and (d) were taken to obtain higher resolution at the expense of coverage.

Both television and infrared instruments are mounted on a scan platform having two axes of rotational freedom. The platform could be stationary or slewed at any combination of 0°, 0.25°, or 1° per second about each axis during observations for image motion compensation. Within the pointing and slewing constraints of the scan platform, four basic types of television picture sequences were used (Fig. 4): (i) a 22-picture photomosaic taken while leaving Phobos at a range of 400 to 600 km; (ii) a 22-picture strip taken while either approaching or leaving Phobos at ranges as close as 300 km; (iii) a 16-picture, high-resolution strip taken at ranges between 130 and 200 km; and (iv) a 10-picture, high-resolution strip at closest flyby. Since picture sequences were transmitted to the spacecraft as much as a week before encounter, the sequences were designed to accommodate possible differences in actual VO-1 and Phobos positions from predicted values. As a result, a total of 232 pictures were planned with only 150 expected to contain useful data.

In spite of the fact that the picture sequences transmitted to VO-1 were designed to account as much as possible for position errors of VO-1 relative to Phobos, the location of Phobos in the first 22-picture mosaic indicated that relative position errors were building more rapidly than anticipated. It was apparent that the mass of Phobos (*GM*) used in picture planning was too large and that, unless the command loads on board the spacecraft were corrected, the remaining high-resolution sequences would be lost. Therefore, mission operations were performed in an adaptive mode. The navigation team produced a new mass estimate from radio data and recomputed instrument pointing on a daily basis. Then, new commands were transmitted daily to override the sequences stored in the spacecraft computer. In these overrides it was not necessary to completely replace the stored commands, only to change the starting time or starting platform position for each sequence. For the second normally planned spacecraft commanding on 25 February, the mass was known with sufficient accuracy so that no overrides were needed.

The success of the adaptiveness of the mission is substantiated by the fact that 125 pictures were received containing data out of the 150 pictures expected to contain data. The small data loss occurred primarily on 19 February, before the mission operations entered an adaptive mode. A 16-picture, high-resolution strip was taken along the terminator of Phobos rather than a few kilometers lower on the illuminated surface as planned. On 20 February the first estimate of the mass of Phobos was obtained. Commands for the high-resolution strip planned for this date were revised, and a spectacular picture sequence of Phobos at 110 km was obtained. These encounter operations were by far the most demanding of any interplanetary spacecraft exploration to date in terms of navigation performance. Since Phobos has a mean radius of only 11 km and was only partially illuminated as viewed during flyby, the spacecraft position relative to Phobos had to be known to an accuracy of a few kilometers. This accuracy level is equivalent to a timing error of 1 or 2 seconds since the relative velocity was about 2.0 km/sec.

Preliminary processing of the encounter data has given an estimate of *GM* of 0.00066 ± 0.00012 km^3/sec^2 [standard deviation (σ) of 3]. Assuming a volume of 5000 ± 900 km^3 (3σ), a mean density of 1.9 ± 0.6 g/cm^3 (3σ) is obtained. This volume, somewhat smaller than that determined from Mariner 9 imaging data (*3*), is indicated by the Viking data and is within the uncertainty of the Mariner 9 value. The resulting mean density is consistent with material similar in composition to type I carbonaceous chondrites, as are the spectral reflectance (*4*) and the absolute albedo of the satellite (*5*). The stated density uncertainty includes both mass and volume contributions.

The imaging data obtained during the encounter period were spectacular. The improved resolution (tens of meters) revealed the presence of small positive features (hummocks), small craters with bright ejecta blankets, dark material on the floors of some craters, large variations in topography, and an abundance of linear features resembling crater chains. Crater densities appear to be close to the saturation limit for craters as small as 20 m in diameter.

A composite of five pictures taken at a range of about 500 km as VO-1 was leaving Phobos is shown in Fig. 5. Most of this part of Phobos was not imaged well by Mariner 9. A vast network of striations is seen at the top (north) of the picture. Other linear crater chains which resemble secondary craters are seen run-

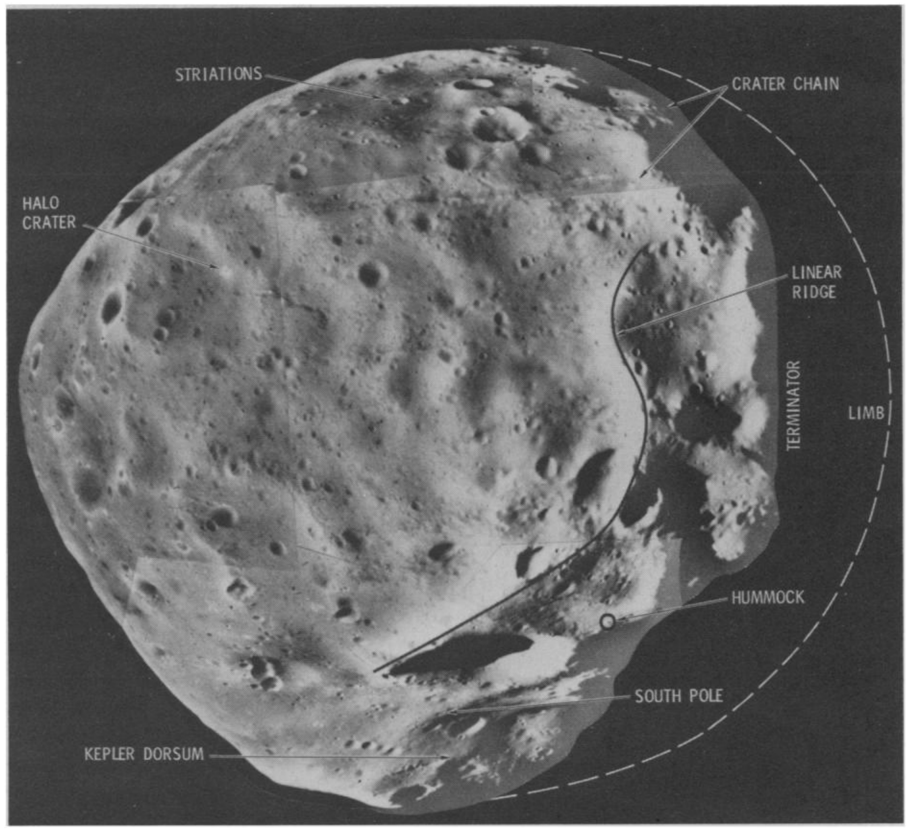


Fig. 5. A photomosaic typical of a 22-frame photomosaic taken as VO-1 was leaving Phobos. Three of these departure photomosaics were taken during the 10-day encounter period (pictures 242A04, 242A06, 242A19, 242A20, and 242A21).

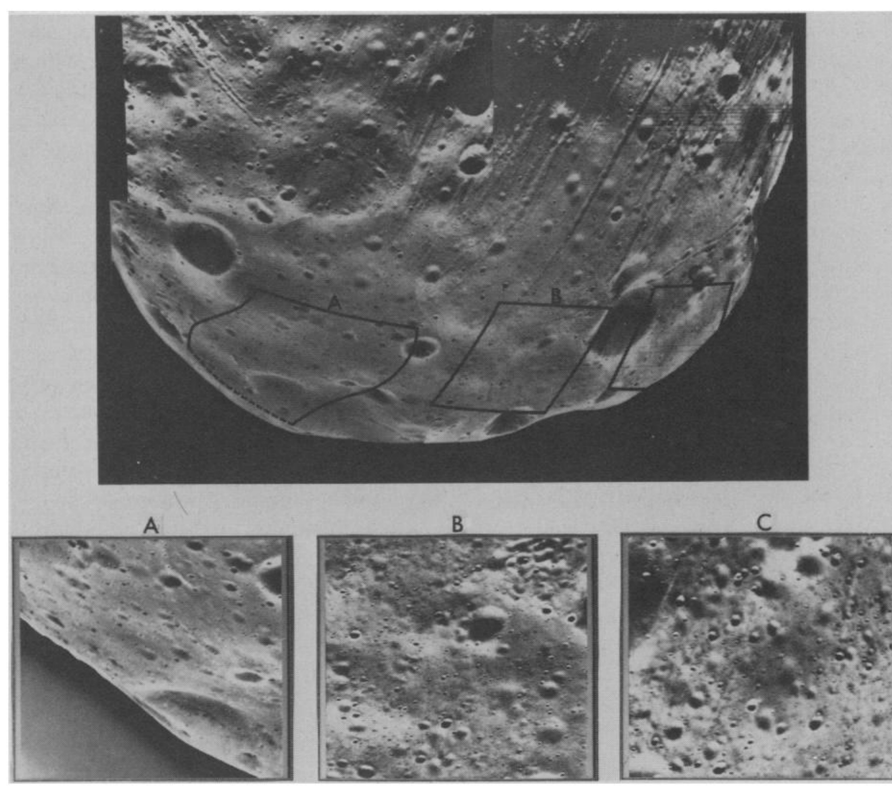


Fig. 6. The photomosaic on top is typical of a 22-picture strip taken as VO-1 was approaching Phobos (pictures 248A01, 248A02, 248A04, and 248A05). Two of these strips were taken on other approaches and two were taken on other departures during the 10-day encounter period. (A-C) The three pictures on the bottom are part of a 10-picture, high-resolution strip which covered the areas labeled *A*, *B*, and *C* indicated on the top of the figure (pictures 244A03, 244A04, and 244A06).

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*).

R. H. TOLSON
NASA Langley Research Center, Hampton, Virginia 23665

T. C. DUXBURY, G. H. BORN
E. J. CHRISTENSEN, R. E. DIEHL
D. FARLESS, C. E. HILDEBRAND
R. T. MITCHELL, P. M. MOLKO
L. A. MORABITO, F. D. PALLUCONI
R. J. REICHERT, H. TARAJI
Jet Propulsion Laboratory, California Institute of Technology, Pasadena 91103

J. VEVERKA
Laboratory for Planetary Studies, Cornell University, Ithaca, New York 14853

G. NEUGEBAUER
Physics Department, California Institute of Technology

J. T. FINDLAY
Analytic Mechanics Associates, Inc., Jericho, New York 11753

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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.