References and Notes

1. T. A. Mutch, A. B. Binder, F. O. Huck, E. C. Levinthal, E. C. Morris, C. Sagan, A. T. Young, *Icarus* **16**, 92 (1972).
2. F. O. Huck, H. F. McCall, W. R. Patterson, G. R. Taylor, *Space Sci. Instrum.* **1**, 189 (1975).
3. F. O. Huck and S. D. Wall, *Appl. Opt.* **15**, 1748 (1976).
4. M. Carr *et al.*, *Science* **193**, 766 (1976).
5. The left side of the footpad picture contains two particularly interesting features. Neither is a real surface feature, since they do not appear in later images of the same area. The first picture was taken about 25 seconds after touchdown. In the first 75 lines of the picture, which took 15 seconds to acquire, there are a large number of fine, bright striations in the image. The effect is similar to what one would expect if the scene illumination were varying markedly from line to line; that is, on a time scale of 0.2 second. The cameras show no electrical anomalies and there were no activities scheduled on the lander which might have caused electrical interference. These lines might be the result of a turbulent cloud of fine dust raised by the lander's retrorockets. Since the lines are brighter than the scene, the dust must, in this explanation, be between the camera and the surface region viewed. The scene detail is not degraded. The turbulence would have to vary very rapidly, and, to the extent that the effect influences entire scan lines, the turbulence would have been correlated over distances of 75 cm. Dust seems to be a plausible explanation, although we have not yet completed our analysis of the time and space variations of these early digital data. The second feature is a distinct vertical dark band crossing the picture. Several explanations might be proposed. First, the dark band could be the shadow of the lander's parachute passing the lander. However, the duration of the shadow is inconsistent with the diameter of the parachute and the wind velocity. Second, it is possible that the band could be the shadow of a martian cloud, in which case other similar bands should be seen as the mission progresses. Through sol 7 no other such bands have been detected. Third, the band could be produced by clods of regolith ejected during descent maneuvers, rapidly deposited on the camera window and slowly sliding off. However the time delay between landing and the appearance of the dark band seems to rule out this explanation. Finally, the dark band could be the shadow of a cloud of dust raised by the landing. This model has been investigated and is consistent with the parameters of the landing if the cloud is roughly 100 m across and 200 m above the surface. Applying the Stokes-Cunningham equation to the particles in the cloud yields an upper limit on particle diameter of roughly 200 μm, a plausible value.
6. E. C. Morris, T. A. Mutch, H. E. Holt, *Atlas of Geologic Features in the Dry Valleys of South Victoria Land, Antarctica; Possible Analogs of Martian Surface Features* (U.S. Geological Survey Interagency Rept.; Astrogeology 52, 1972).
7. E. Morris and E. Shoemaker, *Icarus* **12**, 188 (1970).
8. R. Arvidson, R. Drozd, E. Guinness, C. Hohenberg, C. Morgan, *Proceedings of the 7th Lunar Science Symposium*, in press.
9. H. Moore, R. Pike, G. Ulrich, "Lunar terrain and traverse data: Lunar roving vehicle design study" (U.S. Geological Survey, informal report, 1969).
10. C. Sagan *et al.*, *J. Geophys. Res.* **78**, 4163 (1973); *Icarus* **17**, 346 (1972); J. Veverka *et al.*, *ibid.* **21**, 317 (1974).
11. The Viking cameras record picture information on one or more of 12 silicon photodiodes positioned in the focal plane. The photodiodes are sensitive to light from approximately 0.4 to 1.1 μm in wavelength. Six of the diodes are covered with interference filters which transmit light only in selected wavelength ranges. In acquiring a color picture, data are recorded with three photodiodes which have blue, green, and red filters. Three filtered photodiodes in the near infrared are used to acquire infrared imagery. Color data returned to the earth are used in the laboratory to modulate the intensities of red, green, and blue light ray bundles which are simultaneously scanned over a sheet of color film. Because the voltages recorded by the diodes are a complex function of the diode sensitivities, the filter characteristics, and the atmospheric transmission, it is necessary to scale the relative contributions of each of the three channels to compensate for these effects. The necessary compensation has been calculated in two substantially independent ways which yield similar results. One method depends on prelaunch measurements of the relative spectral responsivities and of the absolute response to a broadband light source to compute the compensation required for equal output for a neutral gray reflecting scene. This assumes that the cameras are stable and that the atmospheric attenuation is negligible. The second method depends on the measured camera response to viewing a reference target (Fig. 4) on the lander top. This target has red, green, and blue color reference patches and also 11 gray patches with integrated reflectances between 0.1 and 0.9. The color compensation is adjusted to optimize the target reproduction; then that compensation is applied to the scene. The disadvantage of this technique is the uncertainty in the human judgment of the "best" reproduction of the target. Both techniques are complicated by the fact that some of the interference filters have small "leaks." For example, the blue filter transmits a small amount of light in the infrared. An object in the scene which reflects large amounts of light in the infrared will appear deceptively bright when imaged with the blue diode. In order to determine such spurious contributions from the scene it is necessary to obtain both a color and an infrared picture of the same scene under approximately the same illumination conditions, and then to balance the colors in a manner which is empirically consistent with the data. Among other reasons for accepting the reality of the colors portrayed, however, is the correct rendering of the gray spacecraft surface and the orange cables.
12. A. Dollfus, *Ann. Astrophys. Suppl. 4* (1957) (NASA Tech. Transl. TT-F-188); A. Binder and D. Cruikshank, *Commun. Lunar Plan. Lab. 193* (1964); R. A. van Tassel and J. W. Salisbury, *Icarus* **3**, 264 (1964); C. Sagan, J. P. Phaneuf, M. Ihnat, *ibid.* **4**, 43 (1965); J. B. Pollack and C. Sagan, *Space Sci. Rev.* **9**, 243 (1969).
13. O. B. Toon, J. B. Pollack, C. Sagan, *Cornell Univ. Rep. CRSR 639* (1976); *Icarus*, in press.
14. R. L. Huguenin, *Icarus* **28**, 203 (1976).
15. T. Thorpe, *ibid.* **20**, 482 (1973); personal communication.
16. J. Pollack, *Icarus* **6**, 42 (1976).
17. S. Hess *et al.*, *Science* **193**, 788 (1976).
18. F. O. Huck, S. D. Wall, E. E. Bucher, *NASA TND-7668* (1974).
19. A. Nier *et al.*, *Science* **193**, 786 (1976).
20. T. Owen and K. Biemann, *ibid.*, p. 801.
21. C. Sagan and J. Lederberg, *Icarus* **28**, 291 (1976).

22. A large number of people have made substantial contributions to this report, in areas of mission design and science analysis. In a very real sense, these persons should be considered coauthors. They include R. E. Arvidson, P. Avrin, C. E. Carlston, R. D. Collie, N. Coradini, R. E. D'Alli, E. W. Dunham, P. L. Fox, S. U. Grenander, E. A. Guinness, B. W. Hapke, J. W. Head, K. L. Jones, R. A. Kahn, B. K. Lucchitta, D. Nummedal, D. C. Pieri, C. W. Rowland, R. S. Saunders, R. H. Stockman, R. B. Tucker, S. D. Wall, and M. R. Wolf. Andrew T. Young played an important role in the early design studies of the lander imaging system. A number of college undergraduates assisted in the operational phase of the investigation. They include A. L. Chaikin, R. G. Cooper, W. E. Dieterle, C. Eberspacher, F. D. Eckelmann, Jr., E. A. Hildum, H. W. Printz, D. W. Thompson, and J. C. Thompson. Their participation was made possible by support from the Alfred P. Sloan Foundation and by the NASA Planetology Office. Because the success of each science investigation is crucially dependent on the efforts of the 750 members of the flight team headed by J. S. Martin, Jr., Viking project manager, and A. Thomas Young, Viking mission director, as well as the 10,000 contractor employees who designed and built the spacecraft, its components, and support equipment, our acknowledgement should also include the 10,000 signatures in the microdot carried to Mars on the spacecraft (Fig. 4). Design and manufacture of the Viking lander cameras was performed by the ITEK Corporation, with active cooperation by Langley Research Center and Martin Marietta Corporation. The Image Processing Laboratory, Jet Propulsion Laboratory, is responsible for special processing of imaging data returned from Mars to the earth and processed the images in Figs. 2, 5, 7, 8, and 10. The images in Figs. 1 and 4 were processed with the real-time software developed by the Data Systems Division of JPL. Financial support for the work of team members was provided by the NASA Viking Project Office.

30 July 1976

Composition of the Atmosphere at the Surface of Mars: Detection of Argon-36 and Preliminary Analysis

Abstract. *The composition of the martian atmosphere was determined by the mass spectrometer in the molecular analysis experiment. The presence of argon and nitrogen was confirmed and a value of 1 to 2750 $\pm$ 500 for the ratio of argon-36 to argon-40 was established. A preliminary interpretation of these results suggests that Mars had a slightly more massive atmosphere in the past, but that much less total outgassing has occurred on Mars than on Earth.*

The objective of the Viking molecular analysis experiment is twofold: to detect and identify the organic compounds, if any, present in the surface of Mars, and to determine periodically the composition of the lower atmosphere (*1*). The central part of the instrumentation for this experiment is a mass spectrometer, coupled to a gas chromatograph for the organic analysis and, by way of a molecular leak, to a gas sample reservoir. Although the instrument was designed primarily for the detection of organic compounds in the gas chromatographic mode (*2*), the mass spectrometer's high sensitivity (dynamic range, six to seven orders of magnitude), high mass range (m/e 12 to 200), and resolution (1 : 200 at m/e 200; better at lower mass) were used to advantage in determining the composition of the atmosphere, particularly its minor constituents. The penalty one pays for resolution and sensitivity is a certain loss of accuracy, mainly because the residual background in the instrument becomes more significant and the long-term reproducibility of the fragmentation pattern is lowered.

Since the more important questions concerning the composition of the martian atmosphere centered around the minor components and certain isotopic ratios, an attempt was made to optimize the experiment toward that goal. In particular, the detection of even traces of N_2 was deemed to be extremely important because previous data (*3*) suggested that it must be a minor component or could be almost completely absent (*4*). One of the major problems in a mass spectromet-

Table 1. Preliminary data on the abundances of gases detected in the martian atmosphere.

Component*	Abundance (%)
Carbon dioxide	95
Oxygen	0.1 to 0.4
Nitrogen	2 to 3
Argon	1 to 2
$^{36}Ar/^{40}Ar$ ratio	1 : 2750 ± 500

*Variable amounts of water, 0.16 percent carbon monoxide, and 0.03 ppm of ozone have been found in the martian atmosphere by ground-based or spacecraft observations [see (7) for references]. Because of surface absorption the mass spectrometric data on H_2O are rather meaningless. The reasons for the CO remaining undetermined are mentioned in the text, and ozone is far below our detection limit.

ric determination of N_2 in the martian environment is the interference of CO^+ (from CO or CO_2) with the ion current of N_2^+ at *m/e* 28. For this reason the gas reservoir of the instrument is coupled via separate valves to two cavities, one containing Ag_2O and LiOH, for the oxidation of CO to CO_2 and absorption of all CO_2, and the other containing $Mg(ClO_4)_2$ for the removal of the resulting water. During the fourth and fifth day after the landing of Viking 1 (20 July 1976) a total of six atmospheric analyses were performed at approximately 6-hour intervals. In the first four of these analyses, CO and CO_2 were removed; in the last two analyses, samples of unaltered atmosphere were used. During the third analysis the spectrometer shut down temporarily, leaving us with a total of five sets of mass spectral scans. Analysis of these spectra gave the averaged results shown in Table 1.

It is clear from these results that the N_2 content is consistent with earlier limits (*3*) and corroborates the results of the upper atmosphere analysis (*5*) performed during the descent of the Viking 1 lander. The argon content is much lower than most recently suggested (*6*) and again supports the value found for the upper atmosphere (*5*).

Of most importance is that the high sensitivity of our mass spectrometer permitted the determination of the abundance of ^{36}Ar which was found to be about ten times lower than the value corresponding to the terrestrial ratio of ^{36}Ar to ^{40}Ar. Neon, krypton, and xenon could not be detected at the limits shown in Table 2. It should be pointed out that for this preliminary analysis the quoted detection limit of neon is higher than the amount of ^{36}Ar actually determined. This is because of the low instrument background and little interference at *m/e* 36 (the absence of a corresponding signal at *m/e* 35 excludes any contribution from HCl) and because of the finite contributions of $^{40}Ar^{2+}$ to *m/e* 20 even at 45 ev.

Low concentrations (less than a few percent) of CO cannot be detected with our system, because of the interference by the large amount of CO_2 in the two analyses of the unmodified atmospheric sample and the concomitant removal of CO when removing the CO_2 in the analyses where it was exposed to Ag_2O. Also, the determination of O_2 is reliable only in the unaltered atmosphere, because of the possibility that some of the Ag_2O produces O_2. For this reason the value for O_2 in Table 1 is from only two measurements.

The determination of other minor constituents, including the isotope ratios for N_2, must await further refinement of the data and additional analyses, which are planned. The abundances of ^{13}C and ^{18}O as determined from the *m/e* 44, 45, and 46 signals appear to be equal to the terrestrial values within the accuracy of our preliminary measurements.

At this stage of the analysis and acquisition of data, it would be premature to draw any firm conclusions regarding the outgassing history of the planet. We can, however, relate some of our results to a theoretical consideration of this problem using ideas developed in anticipation of the experiment (*7*).

The noble gases provide a particularly useful measure of the degree of planetary outgassing. The report by Istomin and Grechnev (*6*) that the martian atmosphere might contain as much as 35 percent ^{40}Ar was widely interpreted to indicate that Mars had outgassed as thoroughly as Earth, and led to the prediction that massive amounts of concurrently produced volatiles had either escaped from the planet or were presently buried in the regolith (*8*). The discovery that the ^{40}Ar abundance is only 1 to 2 percent of the present atmosphere indicates that the other volatiles should be proportionately reduced in such models. But the fact that the $^{36}Ar/^{40}Ar$ ratio is less on Mars than it is on Earth by a factor of 10 suggests that the interpretation of martian outgassing may not be quite so straightforward. The ^{40}Ar may be anomalously abundant on Mars. It should be safer to scale the abundances of other volatiles relative to ^{36}Ar, the nonradiogenic isotope.

If we compare the absolute abundances of ^{36}Ar on Mars and Earth, taking ratios of the mass of gas to the mass of the respective planet, we find that the amount in the martian atmosphere is approximately 100 times smaller than the terrestrial value. This implies that the total degassing of Mars is less complete than that of Earth by about the same factor, if we ignore the possibility of ^{36}Ar escape. The ratios $CO_2/^{36}Ar$ and $N_2/^{36}Ar$ are both roughly ten times smaller in the martian atmosphere than in Earth's inventory of volatiles. It is especially interesting that the relative abundances of N_2 and CO_2 now in the martian *atmosphere* are very similar to the values found in Earth's *inventory*.

Table 2. Upper limits on the gases not detected in the atmosphere.

Gas	Initial upper limit (ppm)*
Neon	10
Krypton	20
Xenon	50

*We expect to decrease these limits for the analysis of the atmosphere under conditions of enrichment of the minor constituents.

One interpretation of these results is that Earth and Mars have a similar bulk composition, so gases are produced in similar proportions but degassing and subsequent weathering on Mars have been much less complete. The present martian atmosphere would then represent about one-tenth the mass of the total outgassed volatiles exclusive of water. The corresponding amount of water is equivalent to a layer a few tens of meters deep.

The missing volatiles may be trapped in subsurface permafrost (H_2O) and at the polar caps (H_2O, CO_2), chemically bound in the soil (nitrates, oxides, carbonates), and some portion must have escaped from the planet (*4*). In this view, the ^{40}Ar abundance represents an anomaly, being roughly ten times more abundant than predicted. This discrepancy could result from several causes, for example, an enrichment of potassium in the martian crust relative to Earth, or a different degassing history for ^{40}Ar compared with the other volatiles, an interpretation that would be consistent with its radiogenesis from ^{40}K.

This Earth-analog model implies that the martian atmosphere was never much more than ten times as massive as it is now, producing a maximum surface pressure of ~100 mbar. But with the possibility that CO_2 can be trapped at the poles and that large amounts of water could be present in the form of permafrost, we leave open the opportunity for cyclical or at least episodic variations of the mean climatic conditions on the planet, which would permit the formation of the sinuous channels by water erosion during temperate periods (*9*).

The relative importance of the various processes for disposing of the missing volatiles, as well as an improved estimate of their total bulk, must await further analysis. It is reassuring to realize that the Viking landers have the capability for performing some of the most critical experiments needed to answer these questions.

TOBIAS OWEN
Department of Earth and Space Sciences, State University of New York, Stony Brook 11794

K. BIEMANN
Department of Chemistry, Massachusetts Institute of Technology, Cambridge 02139

References and Notes

D. M. Anderson *et al.*, *Icarus* **16**, 111 (1972).
2. K. Biemann, *Origins Life* **5**, 417 (1974).
3. C. A. Barth, W. G. Fastie, C. W. Hord, J. B. Pearce, K. K. Kelley, A. I. Stewart, G. E. Thomas, G. P. Anderson, O. F. Raper, *Science* **65**, 1004 (196 A. Dalgarno and M. B. McElroy, *ibid.* **170**, 167 (1970).
M. B. McElroy, *ibid.* **175**, 443 (1972).
A. O. Nier, W. B. Hanson, A. Seiff, M. B. McElroy, N. W. Spencer, R. J. Duckett, T. C. D. Knight, W. S. Cook, *ibid.* **193**, 786 (1976).
6. V. G. Istomin and K. V. Grechnev, *Icarus* **28**, 155 (1976).
7. T. Owen, *Comments Astrophys. Space Phys.* **5**, 175 (19 *Science* **183**, 763 (1974).
8. J. S. Levine, *Icarus* **28**, 165 (1976); T. Owen, *ibid.*, p. 171; F. P. Fanale, *ibid.*, p. 179; R. L. Hugenin, *ibid.*, p. 203.
9. Many investigators suggested this possibility in the wake of the Mariner 9 discovery of the channels. For a review of fluvial processes, see H. Masursky, *J. Geophys. Res.* **78**, 4009 (1973); D. J. Milton, *ibid.*, p. 4037. For a cyclical model of climate history, see C. Sagan, O. B. Toon, P. J. Gierasch, *Science* **181**, 1045 (1973).
10. We thank our fellow team members, D. Anderson, L. Orgel, J. Oro, and P. Toulmin, III, and especially A. O. Nier, for helpful discussions and support. We thank J. E. Biller, A. V. Diaz, D. W. Howarth, A. L. LaFleur, E. M. Ruiz, D. R. Rushneck, and R. Williams for their innovative assistance in the development of this experiment. There are others, too numerous to mention, who have made essential contributions; we thank them all. Supported by NASA research contracts NAS 1-10493 and NAS 1-9684.

30 July 1976

Viking Lander Location and Spin Axis of Mars: Determination from Radio Tracking Data

Abstract. *Radio tracking data from the Viking lander have been used to determine the lander position and the orientation of the spin axis of Mars. The areocentric coordinates of the lander are 22.27°N, 48.00°W, and 3389.5 kilometers from the center of mass; the spin axis orientation, referred to Earth's mean equator and equinox of 1950.0, is 317.35° right ascension and 52.71° declination.*

Analysis of the first few days of radio tracking data from the Viking 1 lander has provided preliminary determinations of the location of the lander on the surface of Mars, the radius of Mars at the landing side, and the orientation of the spin axis of Mars. Determination of these parameters constitutes part of the overall experimental objectives of the Viking radio science team (*1*). These results illustrate the strength of the precise Viking radio tracking data in the determination of astrodynamic constants; they are also important for the interpretation of data from other Viking experiments and for providing accurate reference points for measurements involving topographic parameters.

The Viking lander data used in this analysis consist of approximately 1 hour of Doppler (range rate) measurements at 1-minute count rate on each of the first 3 days after landing, and approximately 10 minutes of ranging data (three range points) on each of the first 2 days after landing. The estimated precision of the Doppler data is better than 1 mm/sec, and that of the ranging data is better than 15 m.

The spin axis orientation and the two components of the lander position in cylindrical coordinates, the longitude and the distance from the spin axis, are best determined from the Doppler tracking data. The third position component, the distance from the equator along the spin axis, is best determined from the ranging data but is subject to large uncertainties if there are even small relative errors in the ephemerides of Earth and Mars. A previously developed special technique (*2*) that uses nearly simultaneous orbiter and lander tracking data has been used to correct the ephemeris errors.

The present analysis consists of a simultaneous solution for five parameters, three lander coordinates and two spin axis orientation components, with all other parameters fixed at their nominal or best-known values. The results obtained for the lander position components, expressed in areocentric coordinates are: latitude, 22.27° ± 0.02°N; longitude, 48.00° ± 0.07°W; radius from the center of Mars, 3389.5 ± 0.3 km. The corresponding value for the latitude in areographic coordinates, frequently used as the reference latitude on maps, is 22.48°N. These results were obtained with a nominal (*3*) and unadjusted spin rate for Mars; any adjustment in spin rate will affect the longitude.

The results indicate that Viking 1 landed about 28 km from its targeted landing site, well within the expected landing dispersions. The radius to the center of Mars is in good agreement (within 1 km) with earlier estimates of the radius at the indicated surface location (*4*), which included consideration of regional topographic variations.

The values determined for the right ascension α_0 and declination δ_0 of the spin axis, referred to Earth's mean equator and equinox of 1950.0 are:

$$\alpha_0(1950.0) = 317.35° \pm 0.06°$$
$$\delta_0(1950.0) = 52.71° \pm 0.01°$$

When compared with the values of Lorell *et al.* (*5*) and of de Vaucouleurs, Davies, and Sturms (*3*), these values and the corresponding uncertainties represent a statistically significant improvement. The larger uncertainty for the right ascension is due to its high correlation with the lander longitude. Since long arcs of lander tracking data provide an excellent data source for these determinations, additional data will improve these estimates and could provide information on pole motion.

W. H. MICHAEL, JR.
R. H. TOLSON
A. P. MAYO, W. T. BLACKSHEAR
NASA Langley Research Center, Hampton, Virginia 23665

G. M. KELLY
Analytical Mechanics Associates, Inc., Hampton, Virginia 23665

D. L. CAIN, J. P. BRENKLE
Jet Propulsion Laboratory, California Institute of Technology, Pasadena 91103

I. I. SHAPIRO, R. D. REASENBERG
Massachusetts Institute of Technology, Cambridge 02139

References and Notes

1. W. H. Michael, Jr., D. L. Cain, G. Fjeldbo, G. S. Levy, J. G. Davies, M. D. Grossi, I. I. Shapiro, G. L. Tyler, *Icarus* **16**, 57 (1972).
2. W. T. Blackshear, R. H. Tolson, G. M. Day, *J. Spacecr. Rockets* **10**, 284 (1973).
3. G. de Vaucouleurs, M. E. Davies, F. M. Sturms, Jr., *J. Geophys. Res.* **78**, 4395 (1973).
4. Topographic map of Mars, M-25M-3-RMC (1 : 25,000,000) (U.S. Geological Survey, Denver, Colo.).
5. J. Lorell, G. H. Born, E. J. Christensen, P. B. Esposito, J. F. Jordan, P. A. Laing, W. L. Sjogren, S. K. Wong, R. D. Reasenberg, I. I. Shapiro, G. L. Slater, *Icarus* **18**, 304 (1973).
6. We thank T. A. Komarek, J. T. Findlay, and G. L. Sievers for assistance and support; E. J. Christensen, C. E. Hildebrand, and H. Hokikian of the Viking navigation team for comparison of independent results, which essentially agree with ours; and the members of the Viking project and Viking flight team, who provided hardware, software, data, and support. Financially supported by the National Aeronautics and Space Administration.

30 July 1976