face of Mercury should be greater than for the lunar case if the impacting bodies are from the same source; thus Mercury should have larger craters for impacting objects of the same mass. Although these two factors are compensating, the effects of velocity probably dominate. Mercurian craters produced by a given impacting mass plausibly could be two to three times larger than their lunar counterparts. This difference would be manifested as an increased number of craters of any given size for the same accumulated fluxes at both bodies. Thus the similarity between the frequency distributions for the Caloris plains units and Apollo 14 site is only apparent, and the implied ages would be different even if the impact flux histories could be assumed to have been the same.
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20. However, at least three less likely alternative configurations of Mercury warrant brief mention. (i) Mercury has only a very thin skin of silicate material (a few tens of kilometers) residing on a substratum of undifferentiated rock (density, ~ 5.5 g/cm^3); the silicates that formed the plains have been drained laterally from over a large area. (ii) The volcanic material of the plains has differentiated in situ into a lunar-like silicate phase and a much denser iron phase; the residual iron must then have moved downward tens if not hundreds of kilometers over a significant portion of the mercurian surface to permit adequate silicate melt to collect near the surface. (iii) The silicate melt that formed the plains was "sweated" out of a uniform, undifferentiated planetary mix maintained at the eutectic temperature throughout most of its mass; it is postulated that the iron component remained solid. In addition to internal difficulties each of these ad hoc possibilities seems poorly suited to reproduce in such detail both the small-scale morphology and the broad three-dimensional form of the lunar maria. The production of extensive volcanic plains requires that the temperature and composition of source materials remain relatively uniform and also requires abundant (if intermittent) flow. Whereas alternative (i) (thin skin) might provide uniform material, it seems implausible that the flow rates for entirely horizontal transport should match closely those of the lunar maria where transport has been in part, at least, vertical. Furthermore, widespread evidence of withdrawal should be present for large areas surrounding the plains units on Mercury. In fact, no such evidence is found. In situ differentiation, alternative (ii), hardly seems likely to produce a uniform melt over such large areas and extended times. A similar objection applies to alternative (iii) (sweat). In addition, vertical transport over thousands of kilometers is implied in that case, making a mare-like flow rate of melt implausible.
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Mercury: Results on Mass, Radius, Ionosphere, and Atmosphere from Mariner 10 Dual-Frequency Radio Signals

Abstract. *Analysis of the radio-tracking data from Mariner 10 yields 6,023,600 ± 600 for the ratio of the mass of the sun to that of Mercury, in very good agreement with values determined earlier from radar data alone. Occultation measurements yielded values for the radius of Mercury of 2440 ± 2 and 2438 ± 2 kilometers at laditudes of 2°N and 68°N, respectively, again in close agreement with the average equatorial radius of 2439 ± 1 kilometers determined from radar data. The mean density of 5.44 grams per cubic centimeter deduced for Mercury from Mariner 10 data thus virtually coincides with the prior determination. No evidence of either an ionosphere or an atmosphere was found, with the data yielding upper bounds on the electron density of about 1500 and 4000 electrons per cubic centimeter on the dayside and nightside, respectively, and an inferred upper bound on the surface pressure of* 10^{-8} *millibar.*

As Mariner 10 flew by Mercury on 29 March 1974, dual-frequency radio transmissions from the spacecraft were monitored on Earth. The instrumentation and techniques for making these measurements have already been described (*1*). Mariner 10's trajectory (*2*) allowed Mercury's mass to be estimated from these data and, because the spacecraft was occulted by the planet, also afforded investigators the opportunity to measure the radius of Mercury and to detect any possible atmosphere or ionosphere. The results of the preliminary analysis of the radio data are presented in this report.

Celestial mechanics. The determination of the mass and the second-degree terms in the spherical-harmonic expansion of the gravitational potential of Mercury is one of the major objectives of the radio-science experiments. Since the analysis of these data is in the initial stages, we present only preliminary findings.

The spacecraft passed about 700 km above Mercury's surface at encounter, along a track inclined about 21° to the equator; only 1 hour from encounter on either side, the spacecraft was 36,000 km from the surface, indicating the very short period during which the Doppler tracking data are sensitive to even the second-degree terms in the gravitational field of Mercury (*3*). Of course, these data are most sensitive to Mercury's mass, and this parameter was estimated with high accuracy as follows: Doppler data from 8 days before to 3 days after encounter were used to estimate the six orbital parameters of Mariner 10 and the mass of Mercury along with various subsets of the second-degree terms of the gravitational potential. In the analyses, the coefficients of all harmonics higher than second degree were always set equal to zero, and the best available knowledge was utilized for (i) the planetary and lunar ephemerides, (ii) the rotation of Earth, (iii) the locations of the radio-tracking stations, (iv) the acceleration of the spacecraft resulting from sunlight pressure, and (v) the effect of the propagation medium on the radio signals. The observed sensitivity of the results to changes in the parameter set as well as in the data set lead us to conclude that the ratio of the mass of the sun to the mass of Mercury is 6,023,600 ± 600 (*4*), in very good agreement with the value obtained earlier from analyses of planetary radar data (*5*).

The postfit residuals from all of the Mariner 10 solutions were remarkably small, the root-mean-square value being typically only a few millihertz (*6*).

We have not yet been able to determine reliably any of the second-degree terms in the spherical-harmonic expansion of the gravitational potential. However, our preliminary analysis in-

Table 1. Mariner 10 Mercury radius.

Occultation	Latitude	Longitude	Solar zenith angle (deg)	Radius (km)	Probable error (km)
Entry	2.3°N	67.4°E	166.7	2439.6	2
Exit	68.4°N	258.8°E	68.4	2438.3	2

dicates that none is larger than the corresponding coefficient for the moon's potential. Further analysis, which will include the calibration of the plasma contribution to the observable deduced from the dual-frequency data, will yield more quantitative results for these harmonic coefficients for Mercury.

The density of Mercury deduced from the mass and radius (see below) determined by Mariner 10, 5.44 g/cm^3, is virtually identical with the value determined from radar observations (*7*). Thus any lingering doubts about its validity should now be removed.

Radio science. The data obtained during the spacecraft's entry into, and exit from, occultation by Mercury have been analyzed to obtain preliminary bounds on the density of Mercury's ionosphere and atmosphere, and to deduce the radius of Mercury at the entry and exit points of occultation. The method used to analyze these open-loop and closed-loop data have been described elsewhere (*8*).

The entry, or immersion, of the spacecraft into occultation occurred on the nightside of Mercury near a latitude of 2.3°N and a longitude of about 67.3°E. The solar zenith angle at the point of occulation was about 166.7°. An analysis of the closed-loop differential, dispersive (S- and X-band) Doppler data from the block 4 receivers at Deep Space Station (DSS) 14 (*1*) showed no indication of any ionospheric layers. The data yielded an upper limit for the electron density of about 4000 electron/cm^3. Emersion, or exit, occurred on the dayside of Mercury near a latitude of 68.4°N and a longitude of 258.8°E. The solar zenith angle was about 68.4°. No clear signature of a dayside ionosphere was observed. The open-loop data from DSS 14 yielded an upper limit for the electron density of about 1500 electron/cm^3 (*9*).

Neither the X-band nor the S-band data provided any indication of propagation effects through a neutral atmosphere, but an upper limit can be inferred from the upper limits of the electron density quoted above. Under the assumptions that any charged particles present on the dayside are the result of photoionization and that the ionosphere would be similar to those of Venus and Mars, it is possible to establish an upper limit for neutral particles near the surface of Mercury of about 10^9 particle/cm^3. If a constituent of the largest reasonable molecular weight, such as argon, is assumed, then the surface atmospheric pressure would be less than 10^{-8} mbar.

Mercury's radius can be deduced for two points on its surface from the observations of the time of extinction and reappearance of the spacecraft radio signal and from the relation at these times of the position of the center of mass of the planet relative to the line of sight from Earth to the spacecraft. The accuracy of the radius determination depends on that of the timing of the occultation events and on the accuracy of the ephemeris of the spacecraft relative to Mercury. From the analysis of the open-loop data obtained during entry and exit, the times for the occultation were determined with an error of less than 0.05 second, corresponding to a projected error in the radius determination of about 250 m. However, the uncertainty still existing in the ephemeris of the spacecraft relative to Mercury is the major source of error in the radius determination. The results are summarized in Table 1, which also shows the latitudes, longitudes, and solar zenith angles at the two occultation points as well as the probable errors of the radius estimates. These uncertainties are based on the variations in the values of the radius when computed with different sets of available spacecraft ephemerides. These uncertainties should eventually be reduced by about an order of magnitude. The value of the equatorial radius based on the entry measurement is very close to the mean radius of 2439 ± 1 km obtained from the analysis of planetary radar data (*5*). The difference in radius between the two determinations from the Mariner 10 data is less than the current uncertainty in each. However, even when these uncertainties are reduced, it will not be possible to use these radius measurements to distinguish any overall flattening of the planet from local variations in its topography.

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3. Appreciable sensitivity to these terms exists only for about 40 minutes, centered on encounter; however, no tracking data exist for the 12-minute duration of the occultation which started several minutes past encounter.
4. The corresponding value for the product of Mercury's mass and the universal constant of gravitation is 22,032 ± 2 km^3/sec^2.
5. Some of the early determinations of the ratio of the mass of the sun to the mass of Mercury from radar data, in chronological order, are: 6,021,000 ± 53,000 [M. E. Ash, I. I. Shapiro, W. B. Smith, *Astron. J.* **72**, 338 (1967)]; 5,983,000 ± 25,000 [W. G. Melbourne and D. A. O'Handley, *Jet Propulsion Lab. Space Programs Sum. 37–53* (1968), vol. 3, p. 1]; and 6,025,000 ± 15,000 (*7*). More recent estimates have been made at both the Massachussets Institute of Technology and the Jet Propulsion Laboratory, a typical value being 6,022,700 ± 3,000 [I. I. Shapiro and R. D. Reasenberg, in "Mariner Mars 1971 Project Final Report," *Jet Propulsion Lab. Tech. Rep. No. 32-1550* (15 July 1973) vol. 4, pp. 460 and 464].
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