MERCURY'S ROTATION PERIOD: PHOTOGRAPHIC CONFIRMATION

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ABSTRACT

Photographic measures of surface features on Mercury have led to a rotation period of 58.663 ± 0.021 *days, agreeing well with the* 58.646-*day period required by a predicted* 2:3 *resonance between the axial and orbital periods. The interpretation of earlier visual and photographic observations which specified the long-held* 88-*day rotation period appears to be partially explained by peculiar characteristics of the observability of various hermographic longitudes. Additionally, the apparent contrast of most of the recorded surface features is found to be marginal for visual observation when viewed through the terrestrial daytime sky. The intrinsic contrast of a relatively conspicuous feature was measured as* 0.20, *a value lower than that of typical markings observed on the moon and Mars.*

Throughout most of this century we have unhesitatingly accepted the axial rotation period of the planet Mercury as being 88 days, or with somewhat less certainty as 87.969 days, an interval precisely equal to its period of orbital revolution about the sun. This 88-day rotation period was first announced in 1890 by the Italian astronomer G. Schiaparelli (1890) following 8 years of visual observations through his modest telescope.

Repeated confirmation was given by several French and American astronomers over the next several decades, but the matter was considered settled when the eminent planetary astronomer E.M. Antoniadi (1934) published his support of the 88-day period. If still further confirmation were needed, it was submitted by A. Dollfus (1953, 1961) in the form of both visual and photographic evidence obtained at the French high-altitude observatory at Pic-du-Midi. It should be noted that the optical interpretation did not stand alone; theoretical arguments suggested that solar gravitational forces acting on a tidal deformation would lock Mercury's axial and orbital periods into synchronism in a manner similar to that of the moon in its orbit about the earth (see Antoniadi, 1934).

With this historical background in mind, one can appreciate the impact of the 1965 announcement by Pettengill and Dyce (1965) that their radar observations of Mercury gave evidence for a rotation period of 59 ± 5 days Almost as interesting as this new discovery itself, was the suggestion by Colombo (1965) that the rotation period might be equal to exactly 2/3 of the orbital period, or 58.646 days. With improved radar measures converging on the 59-day period, Goldreich and Peale (1966), Jefferys (1966), Colombo and Shapiro (1966), and others found that it is indeed possible for Mercury's axial rotation to be locked into a 2:3 resonance with its orbital revolution.

As the case for the 88-day rotation period began to weaken, a closer inspection was made of the earlier visual and photographic records, particularly the French observations (Fournier, Antoniadi, Camichel, Dollfus) which are generally considered to be the most reliable. Cruickshank and Chapman (1967) and Chapman (1967) found that certain visibility relationships had combined in such a way that the historical records could support <u>either</u>

the 88- or 59-day periods, although they assigned greater probability to the latter. (We have studied these visibility factors in some detail and will later discuss their effects on the interpretation of observations). Dollfus and Camichel (1967) and Camichel and Dollfus (1968) have not only noted that the earlier Pic-du-Midi photographic and visual observations would accomodate either period, but they have also introduced recent visual observations which they contend are consistent only with a rotation period of 58.67 ± 0.03 days. Within the probable error, this period is in complete agreement with the 2:3 resonance condition. In concluding this brief review of the retrospective reinterpretation of earlier records, we want to emphasize that to date all evaluations of the rotation period of Mercury have made use of recurrent appearances of recognizable features on the planet's surface; there are no references to direct quantitative observations of rotational motion.

We initiated our own program of photography of Mercury in late 1965, several months after the announcement of Pettengill and Dyce. As an object for telescopic photography, Mercury is among the most difficult in the solar system. Never appearing more than 27° (elongation angle) from the sun, its minute disk must usually be photographed in full daylight. Optimum observing geometry involves a compromise between phase and apparent size, and this occurs when the phase angle is approximately 70°. At this phase the elongation angle has an average value of 20° and the disk is a mere 6 seconds of arc in diameter. The observational difficulty can best be expressed by the limit of our success over the past 2½ years--a total of only 96 useful photographic plates on 64 different dates.

Until March of this year, the results of our photographic program were generally inconclusive, although a pair of plates taken on 6-8 May 1966 strongly suggested the 59-day rotation period. During March and April, however, we were fortunate enough to obtain several more plate sequences in which the daily rotational motion of several surface features across the disk of Mercury could be detected and measured. Rotation periods for 4 of these discrete surface features (tentatively labeled A, B, C, D) are given in Table I.

The observations summarized in Table I give conclusive support to the radar rotation period, denying once and for all the long-held value of 88 days. Making use of the directly derived photographic rotation period, it was now possible to substantially improve this accuracy through the use of an extended time base. Features A, B, and D, and two others (tentatively labeled E and F) were measured at intervals of one (B only) and twelve rotations of Mercury. With this further improvement it was finally possible to make use of a 1942 photograph, taken some 160 rotations earlier at Pic-du-Midi, in which features E and F were identified and measured. Rotation periods derived from the recurrent appearances of features A, B, D, E and F are given in Table II. The weighted mean value for the rotation period is 58.663 ± 0.021 (s.d.), and it will be noted that the 58.646-day rotation period for the 2:3 resonance lock falls just within the computed error.

It must be pointed out that all errors given in Tables I and II are statistical only and do not include any systematic errors that may arise out of photographic phase effects or uncertainty in the diameter of Mercury itself. Such systematic errors are probably the cause of the somewhat large rotation periods given in Table I; however, it is to be expected that they would have a greatly reduced effect on the values given in Table II. We have estimated that a reduction in the accepted diameter of Mercury of 5 percent would remove the discrepancy between Tables I and II. However, uncorrected phase effects could just as likely be the cause.

When it became certain that the axial rotation period of Mercury was approximately 58.6 days, and that it was quite probably locked in the 2:3 resonance with its orbital period, we began a study of observability conditions that might have led to the incorrectly inferred 88-day period. A computer program was prepared to give the hermographic longitude of Mercury's central meridian, the longitude of the terminator, phase angle, elongation angle, ecliptic longitude, and several other parameters of lesser importance all associated with the observability of the planet. The prime meridian is defined as passing through the subsolar point at the instant of perihelian passage on 1 May 1968. The assumed 2:3 synchronous lock would assure redefinition of the prime meridian at every other perihelion passage. We further assume the rotation axis to be perpendicular to the orbital plane. Print outs were obtained at daily intervals for all useful phase angles, which we have taken to lie between 20° and 120°. Now, the orbital periods of Mercury and the earth are such that 54 revolutions of Mercury are almost exactly equal to 13 revolutions of the earth. Therefore, the relative orbital positions of the two planets are repeated at 13-year intervals, and we were able to include all visibility geometry in a 13-year run out of the computer program.

Using phase angle as an observability parameter and selecting 70° as a mean value to represent each elongation, we listed the hermographic longitude of the central meridian and the ecliptic longitude of the planet for each of the 82 elongations (41 evening and 41 morning) that occur during a 13-year interval. The ecliptic carries Mercury alternately north and south of the celestial equator, and so was arbitrarily divided into four latitude zones with each being assigned an observability index: 1 through 4. Thus, for observatories located in the northern hemisphere of the earth, the superiority of each elongation is determined by the ecliptic latitude index: 1 = excellent, 2 = good, 3 = fair, 4 = poor. For telescopes located in the southern hemisphere, the reverse listing would be appropriate: 4 = excellent, 3 = good, etc. Fig. 1 is a graphical representation of the results of this tabulation.

Several important characteristics of Mercury's selective visibility are immediately evident in Fig. 1. All elongations (both evening and morning), favorable to northern hemisphere observatories, tend to accentuate two specific longitudes--90° and 270° (dashed lines)--with each being emphasized for somewhat more than half of the 13-year cycle. Thus, an observer in the northern hemisphere covering only the favorable elongations would be seeing essentially the same regions on Mercury for as long as 7 successive years. The regions around 0° and 180° longitude are particularly unfavorable, being seen only under fair to poor conditions twice during the 13 years. It is now easier to understand why many observers might have concluded that Mercury presents but a single hemisphere to the sun (88 day rotation period). For an observer in the southern hemisphere, however, all longitudes except those near 90° and 270° would be equally well presented and would be seen twice during each 13-year cycle. Therefore, the observable longitudes on Mercury shift rapidly from year to year for a southern hemisphere observer, and had Schiaparelli or Antoniadi made their observations from Africa, Australia, or South America, the true rotation period of Mercury might have been established long ago.

In this analysis we have assumed that the observer can see only the hermographic longitude indicated by the circle in Fig. 1. Of course such is not the case. Not only can regions be studied as far as 40° from the central meridian (unless intercepted by the terminator), but moderately useful observations can be made over a range of phase angles extending from approximately 30° to 110°. Nevertheless, the longitudes indicated in Fig. 1 are typical of the regions most likely to reveal surface features under observing conditions which are less than ideal.

There is yet another factor which contributes to the peculiar pattern governing the observability of Mercury's surface. The eccentricity of Mercury's orbit causes the daily motion of the planet around the sun to vary between 6°.35 at perihelion and 2°.75 at aphelion. Moreover, it happens that the daily motion near perihelion is approximately equal to the daily rotational displacement (6°.14) given by the 58.646-day rotation period. As a consequence of this, the hermographic longitudes of the terminator remain nearly constant at 90° and 270° for 20 consecutive days centered on perihelion. At those times when the curves connecting elongations favorable to our northern hemisphere (large circles) in Fig. 1 are oriented in vertical pairs, perihelion occurs near phase angle 35°, approximately 8 days before and 8 days after the 70° optimum phase angles for the evening and morning elongations, respectively. This causes longitude 90° (or 270°) to appear along Mercury's terminator for about 10 consecutive days during the nominal useful observing interval of certain evening elongations. Then, some 2½ months later during the corresponding morning elongation, the same longitude will be seen on the evening terminator for another 10 consecutive days. A similar pattern occurs for those times when the elongations favorable to our southern hemipshere (small dots) are alined in vertical pairs. In this case perihelion occurs near phase angle 115°, about 18 days from the 70° optimum phase angle. The frequency of occurrence of paired vertical alinement is unequal for those elongations favorable, respectively, to the terrestrial northern and southern hemispheres, as can be seen in Fig. 1. Thus, the conditions producing those characteristic elongations with hermographic longitudes 90° or 270° along the terminator will persist throughout a larger part of the 13-year cycle for those elongations most favorable to our <u>northern</u> hemisphere.

We have shown how a peculiar observability pattern might have misled earlier visual observers into believing that Mercury keeps the same side turned toward the sun. We will discuss now still another factor which must be taken into consideration when attempting to explain the historical visual observations. We refer to the visibility or contrast of the features themselves, and consequently to the reliability of visual observations in general. McGovern, Gross, and Rasool (1965) have studied several sets of visual observations with the conclusion that Mercury's rotation period is 58.4 ± 0.4 days. While we fully agree with the writers' conclusion, we strongly question the means by which they arrived at this result. Specifically, their rotation period was heavily influenced by four pairs of Antoniadi's observations. In examining the published drawings of Antoniadi (1934), we find other observations which are in serious conflict with three of the pairs used by McGovern et al. Thus, the 59-day rotation period could be obtained by selecting only those observations which tend to support it, and by ignoring those which do not.

In studying these contradictory observations further, we have measured the hermographic longitude of a prominent feature, which appears at approximately 320° in 8 of Antoniadi's 20 drawings, and find a dispersion in longitude that extends over an interval of 75°. If we were to assume this dispersion to be due only to random errors of observation, the standard deviation would be 27°, nearly equal to half of the distance from the center of the disk to the limb! We are therefore forced to conclude that at least some of the "accepted" visual observations are completely inaccurate, probably because of marginal visibility of surface features on Mercury. We turn now to direct measures of visibility.

Photographs of Mercury taken in red light on 25 April 1968 show a well-defined feature of non-typical conspicuousness at 240° longitude and located near the center of the disk. Photometric calibration applied at the time to the photographic plates has permitted an evaluation of both the apparent and intrinsic contrasts of this marking. We find an intrinsic contrast of about 0.20, somewhat less than the dark areas on the moon (0.4) and Mars (0.3 in yellow light). However, the <u>apparent</u> contrast of this feature was only 0.08 because Mercury was necessarily observed through the illuminated terrestrial daytime sky. Less conspicuous markings had contrasts less than half as great, and this certainly represents marginal visibility. Typical surface features on Mercury therefore are quite difficult to detect by direct visual observation, and it must remain for high contrast photography to provide the most reliable means available at this time for mapping the surface of Mercury.

Our work with Mercury continues. The 13-year ephemeris and a provisional map of the surface of Mercury will be published in the near future.

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TABLE I

Rotation Periods Derived from the Motion of Surface Features Across the Disk of Mercury at Intervals Less Than a Single Rotation.

Feature	Interval Observed	Observations	Rotation Period (days)
A	25-31 March 1968	3	61.0 ± 0.6
B	23-28 March 1968	3	64.3 ± 2.0
C	28-31 March 1968	2	65.8 ± 5.0
D	6-8 May 1968	2	54.7 ± 11.0
D	5-13 April 1968	5	58.7 ± 1.5
Weighted Mean			61.14 ± 1.68

TABLE II

Rotation Periods Derived from the Recurrence of Surface Features on the Disk of Mercury at Intervals of One or More Rotations.

Features	Interval Observed	Observations	Rotation Period (days)
A	27 Apr ~~68~~ 66-28 Mar 68	4	58.688 ± 0.045
B	27 Apr 66-28 Mar 68	5	58.696 ± 0.055
D	6 May 66-13 Apr 68	7	58.681 ± 0.015
E	10 Aug 42-30 Jan 68	3	58.652 ± 0.010
F	10 Aug 42-30 Jan 68	3	58.654 ± 0.011
Weighted Mean			58.663 ± 0.021

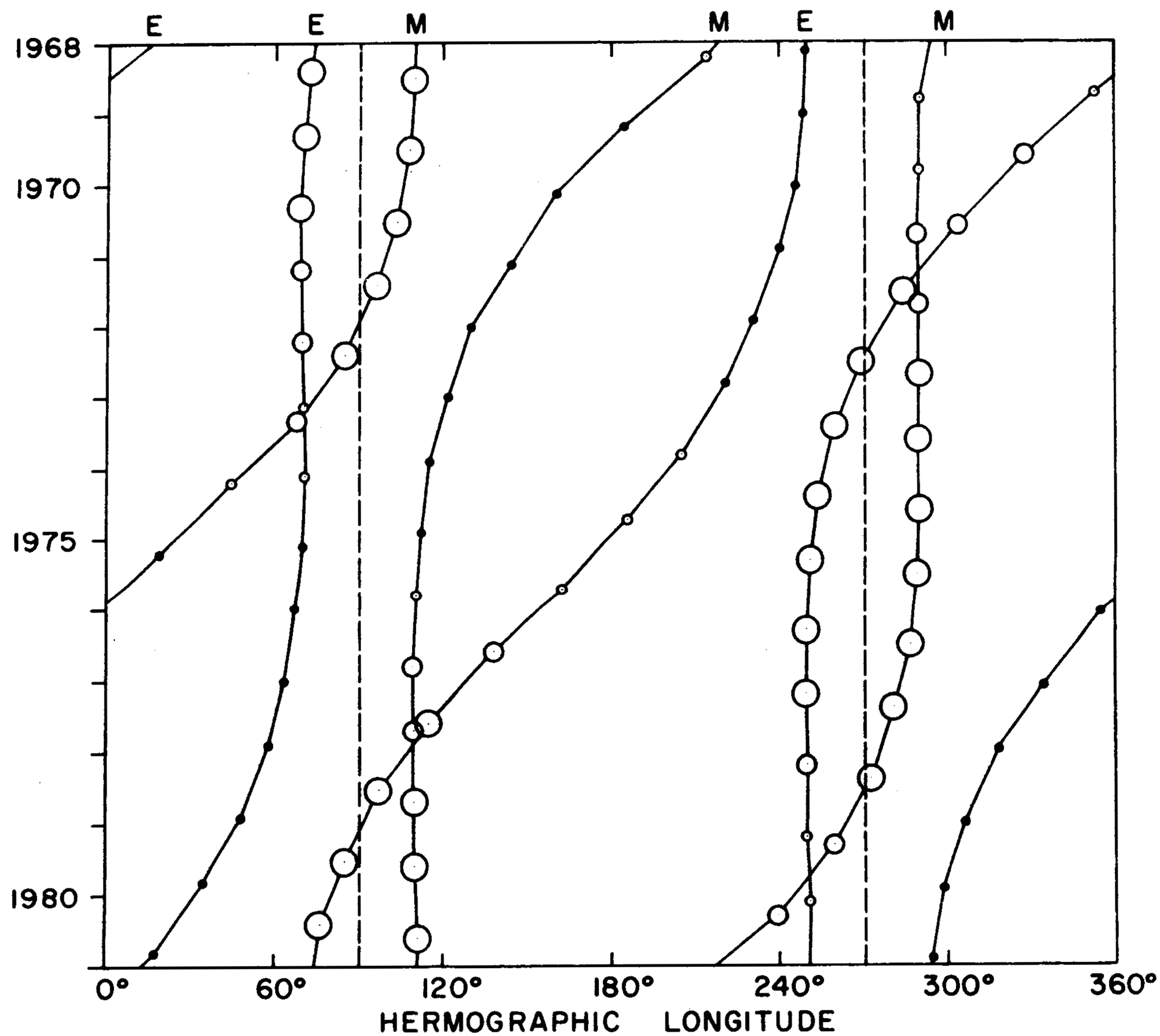

Figure 1. Hermographic longitude of the center of the disk of Mercury at phase angle 70° for all evening (E) and morning (M) elongations throughout a 13-year cycle. Circle size indicates observational favorability for northern hemisphere observatories. An inverse relationship would apply to southern hemisphere observatories.