No. 143 THE PLANET MERCURY: SUMMARY OF PRESENT KNOWLEDGE

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ABSTRACT

Present knowledge is collected on the Mercury orbit, diameter, mass, density, rotation, surface features, atmosphere, polarization, albedo, and color. Comments are presented on problems that may be solved from image resolutions of about 1 km.

1. *Orbit*

The mean orbital distance *a* for 1968 is 0.387099 astr. units *; the eccentricity *e*, 0.205628; and the inclination *i*, 7°.00415. The quantity *a* varies little except for minor periodic terms; *e* varies during several million years from 0.109 to 0.241; *i* (counted with respect to the invariable plane of the planetary system) varies from 4°.5 to 9°.8; while the longitude of the perihelion and the longitude of the ascending node on the invariable plane rotate in periods of respectively 220 and 250 millennia (Brouwer and Clemence 1961). (To these, small relativistic effects must be added.) A plot of the time variation of *e* and *i* for 10^7 years centered on the present epoch, and based on the theoretical analysis by Brouwer and van Woerkom (1950), kindly provided by Drs. E. C. Hubbard, C. Oesterwinter, and C. J. Cohen, is appended. It is unknown how much *a, e, i* may have varied through the *entire* age of the solar system, 4.6-4.7 10^9 years; it is possible that the variations have not been vastly larger than during the past "several million" years for which the perturbation theory is known to be approximately valid.

* The astr. unit is 149,597,892 ± 1.5 km (Muhleman 1969).

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2. *Diameter, Mass, Density*

From micrometric observations and disk-meter measures, particularly during Mercury transits across the solar disk, a diameter of 0.38 Earth was derived. Recently a much more precise radar measure has been obtained (Ash *et al.* 1967), 4868 ± 4 km, or 0.382 Earth.

The first fairly accurate value of the mass was derived by Rabe (1950), 0.0543 Earth ± 0.7%. Improved values were derived (Ash *et al.* 1967) from radar data and by Mulholland (1968) from Mariner V signals, of $6{,}021{,}000^{-1}$ Sun or 0.0553 Earth ± 0.9%, and $5{,}935{,}000^{-1}$ or 0.0561 Earth, respectively. We may therefore conveniently adopt the old Newcomb (1895) result since then used in the Nautical Almanac, $6{,}000{,}000^{-1}$ Sun or 0.0555 Earth ± 1%.

The resulting mean density of the planet is 1.01 Earth or 5.6 cgs ± 1%. Because of the small mass of Mercury (small gravitational compression), it may be directly compared with the uncompressed density of the Earth, 4.2; of Mars, 4.0; and of the Moon, 3.3. There is thus no doubt that density and therefore composition differences of the terrestrial planets are *real*, and that the assumption of near-equality in composition is erroneous. Mercury is composed of 65°-70% by weight (half the volume) of metal phase; and only some 30% by weight of silicate phase.

Two explanations may be advanced for this extraordinary composition.

(a) The accretion process favored the acquisition of metallic constituents, even for the Earth which appears to be more iron-rich than the Sun. This possibility has been examined by Harris and Tozer (1967). Iron can also accrete preferentially at higher temperatures (Anders, 1968).

(b) The planet Mercury was originally 2-3 times more massive, melted internally, resulting in the formation of a metal core and a silicate mantle, all prior to the occurrence of a very luminous phase of the Sun, as postulated by Hayashi (1966), which was responsible for the evaporation to space of most of the silicate mantle.* The discovery of observational evidence for the Hayashi phase of the Sun, either from the surface of Mercury or the surface of the Moon in a comparatively undisturbed highland region (such as exist between Tycho and Snellius; Kuiper, 1954 and 1959), would, of course, be of very great interest for charting the early evolution of the solar system.

A choice between processes (a) and (b) could perhaps be made now. E.g., an interpretation of the dark spots on Mercury (as lava fields) would favor process (a); and a more detailed study of the accretion process in the solar nebula near Mercury could be made with the solar luminosities suggested by Hayashi (1966), but a time scale *extended* to allow for the considerable angular momentum of the solar nebula, neglected in the studies to date.

3. *Rotation*

Visual observations of the planet and its spots since Schiaparelli (1890) showed that the period of rotation was *not* short (about a day), but *long,* possibly as long as the orbital period, 88 days. Because of the known synchronous rotation of the Moon and the Jupiter satellites, it probably did not occur to anyone that the long period could be anything but synchronous. Proximity of Mercury to the Sun fitted with this concept. The discovery by radar of the period, 59 days ± 3 (Pettengill and Dyce 1965; Shapiro 1967), ⅔ of the orbital period, was, of course, of extraordinary dynamical and cosmological interest. It led to a series of theoretical studies (Colombo and Shapiro 1965; Peale and Gold 1965; Colombo 1965; Goldreich and Peale 1966), showing the conditions required for this type of synchronization. The considerable eccentricity of the orbit and the resulting near-synchronous rotation near perihelion (when tidal friction is largest) seem to suffice, but do not exhaust all questions relative to the evolution of the system; cf. also Kaula (1968). In particular, the large secular variations in the orbital eccentricity pose problems.

4. *Surface Features and Rotation*

With the rotation period known to a few percent, all visual and photographic observations of the past 75 years could be re-examined and combined into one map. This task was undertaken by Camichael and Dollfus (1968) who added important observations of their own, made under the excellent conditions of the Pic du Midi, France. On the basis of all the reliable drawings and photographs, they concluded that the period of rotation is, within a precision of better than ± 0.01 days, indeed just ⅔ of the orbital period, 58.646 days. The resulting map, drawn on the Mercator projection, is reproduced in Fig. 1 (South up). This map may be compared with a map of Mars drawn by J. Focas, also at the Pic du Midi, in 1958, probably the most reliable and detailed map of Mars derived from earth-based observations (cf. Fig. 2). It may further be compared with a similar map drawn for the Moon, composed at this Laboratory by Mrs. B. Vigil* (Fig. 3), and with maps of the Galilean satellites of Jupiter drawn by Lyot (reproduced in Fig. 4) (telescopic views: South up). While intercomparison between these maps is hampered by the low resolution in Figs. 1 and 4, some conclusions may be drawn. A suitable working hypothesis appears to be that all dark areas on the Moon, Mars, and Mercury are lava fields. For Mars this hypothesis was discussed previously (Kuiper 1957); it appears compatible with seasonal and progressive changes in visibility, attributable to moving aeolian deposits (*loc. cit.*). Some areas on Mars, like the Solis Lacus region, appear remarkably similar to the Mare Australe region on the Moon. The Mercury spots seem more Mars-like than lunar; the bulbous appearance of the lunar spots, attributable to impacts, appears absent or minor. The bright areas of Mercury might, in part, be due to crater ray systems.

* The writer reviewed this possibility in a lecture before the A.G.U., Washington, D.C., April 1969.

* The coordinate system used is that of the recent ACIC map, using the Mercator projection; the half tones are based on available photography.

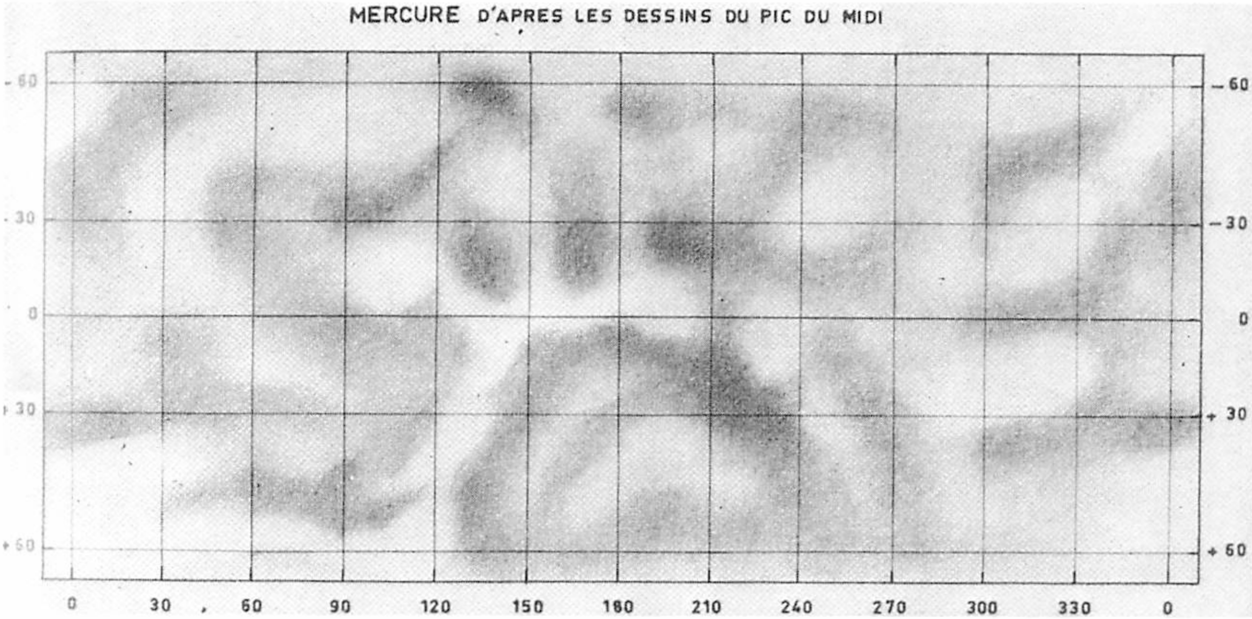

Fig. 1 Mercator map of Mercury spots, *S* up (after Camichel and Dollfus 1968).

5. *Atmosphere*

Early attempts of deriving information on the presence of an atmosphere on Mercury from polarization measurements near the cusps of the planet were reviewed by O'Leary and Rae (1967) and found to need revision. They concluded that the polarimetric observations suggest an upper limit of 1 mb for the surface pressure, while the similarity of the polarimetric and photometric properties of Mercury and the Moon suggested an upper limit of 10^{-5} mb. The earlier results were also criticized by Hodge (1964).

Direct spectroscopic tests include those of Moroz (1965) who believed to have found CO_2 in the amount of 0.3-7 gm/km^{-2}; Binder and Cruikshank (1967) who found no evidence for the presence of CO_2 on Mercury from spectra in the 1.6 μ region; Belton, Hunten and McElroy (1967) who observed the 1.049 μ band and placed the upper limit of 5 m-atm of CO_2 on the planet, equivalent to a surface pressure less than 0.35 mb; Bergstralh *et al.* (1967) who used the 1.2 μ bands and derived an upper limit of 0.58 m-atm or a surface pressure of 0.04 mb; and Kuiper, Cruikshank, and Fink (1970) who observed the planet between 1μ-4μ and found an upper limit for CO_2 of 0.01 mb. Yet CO_2 would probably be the first gas to look for in view of the composition of the Mars and Venus atmospheres. Radiogenic A^{40} would be much harder to detect.

The low temperature occurring on the dark side of Mercury, approximately 100°K, and the much lower temperatures that must exist in shaded areas and crevices near the Mercury poles, must act as cold traps which will reduce the CO_2 pressure to amounts that are imperceptibly small spectroscopically. E.g., for 80°K the surface pressure would be 10^{-7} mb for CO_2 and 10^{-22} mb for H_2O; for A^{40} the saturation pressure would be 400 mb so that small amounts of radiogenic argon could possibly be present.

6. *Polarization, Albedo, Color*

As is well known, these three quantities are remarkably similar to the Moon. For polarization we refer to the classical work of Lyot (1929) who showed that the Mercury polarization curve is intermediate between those of the waxing and waning phases of the Moon (which differ slightly, owing to the uneven distribution of lunar maria). The visual albedo of Mercury is 7% (like that of the Moon); and the color is remarkably similar as well. Harris (1961) cites B - V for the Moon +0.92 and for Mercury +0.93, as compared to the solar value +0.63. Results for the full spectral range of 0.31 to 1.0 μ are given by Irvine *et al.* (1968), together with a plot of lunar values by Harris. The agreement is very close. Presumably, the Mercury surface is covered, as is the case for the Moon, with finely-

Fig. 2 Telescopic Mercator map of Martian surface features, *S* up (after Focas in Dollfus, *Planets and Satellites*, Ch. 15, 1961, Plate 19).

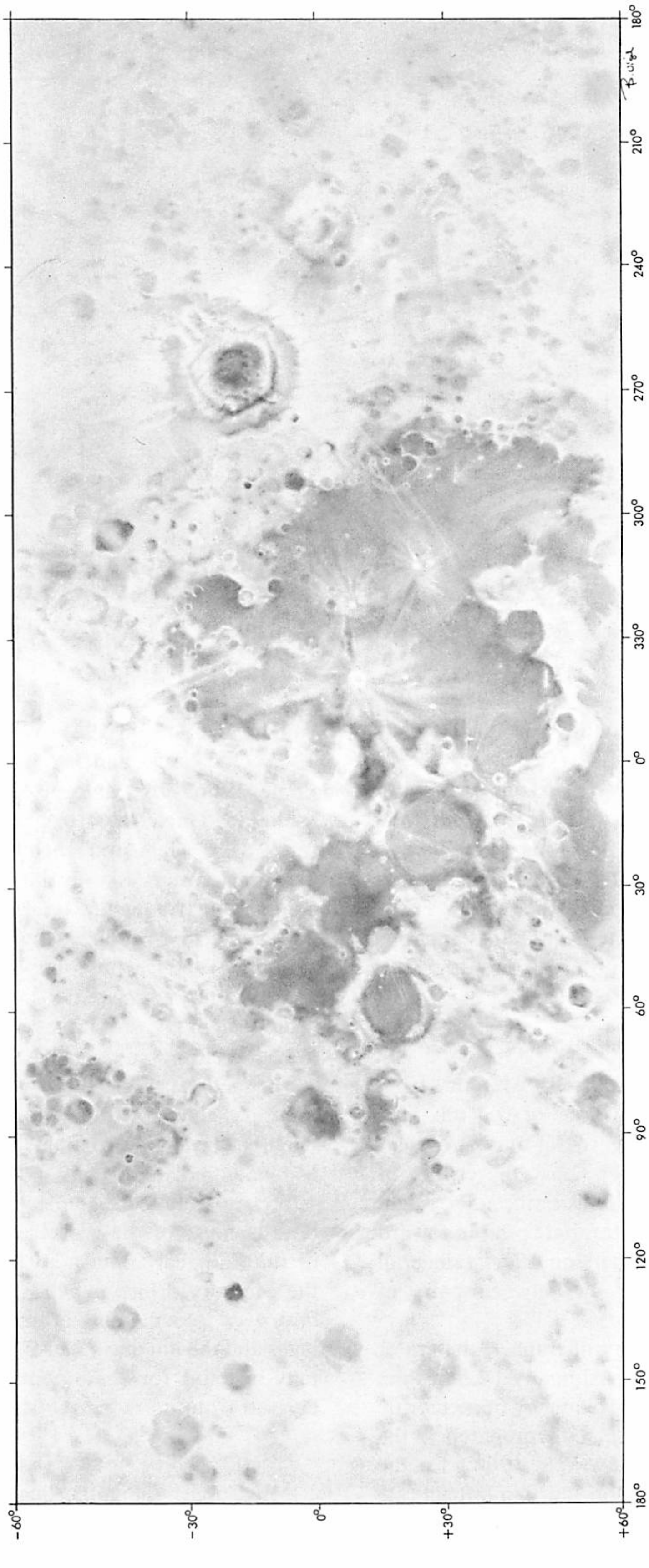

Fig. 3 Mercator map of Moon, *S* up, by Barbara Vigil.

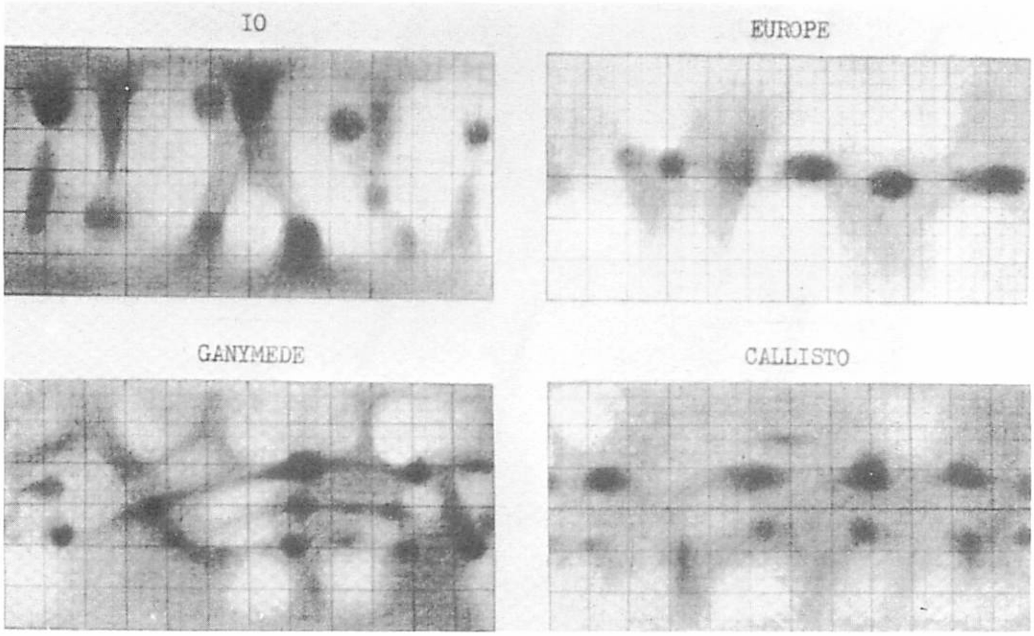

Fig. 4 Mercator map of Jovian satellites (after Lyot, *Planets and Satellites,* Ch. 15, 1961, Plate 40).

crushed silicate material, roughly basaltic in composition.

The radar cross section (or radar geometric albedo) measured at 70 cm (430 Mc/sec) is 6-7% of the physical cross section, as compared to 7% for the Moon (Pettengill *et al.* 1967); and the scattering law is also very similar to that of the Moon. These authors point out that similar radar cross sections have been found at other observatories for 700, 1295, and 2388 Mc.

7. *Craters and Debris Layer*

Owing to the smaller distance of Mercury from the Sun, compared to the Moon, of 0.4 a.u., the energy of impact by small asteroidal masses of very large meteorites will approach 2.5× the energy of corresponding lunar impacts. This ratio, 2.5×, might also apply to smaller meteorites that spiral in toward the sun by the Poynting-Robertson effect (since all relative motions are scaled up between pairs of orbits of given eccentricities).

With the increased energy of impact, the crater area per impact will be approximately $(2.5)^{2/3} =$ 1.8× that on the Moon. The frequency of meteoritic impacts, however, will be *reduced,* compared to the Moon, by a factor > 10× (Arnold 1964) for the same dynamical reason that the Martian impact rate is some 20 times larger than the lunar rate (cf. Anders and Arnold 1965; Witting, Narin, and Stone 1965; Öpik 1951 and 1963; Kuiper, Strom, and Le Poole 1966). As a result craters on Mercury of asteroidal (meteorite) origin will be comparatively rare, > 10× less frequent than on the lunar maria. Cometary craters, like Tycho on the Moon, may have comparable frequency on Mercury since they are expected to be produced by near-parabolic comets (Kuiper 1965) whose impact frequency per unit area will not vary greatly in the inner parts of the solar system. A few large ray systems on Mercury may therefore be expected. Very small craters (d < 10 meters) might be *formed* more frequently on Mercury than on the Moon; but the disturbed (debris) layer, approximately 1 meter thick on the Moon (predicted, Öpik 1960; observed, Kuiper 1965) is likely to be somewhat thicker on Mercury, both because of the greater density near the planet of the Zodiacal Cloud and the high eccentricity of the Mercury orbit; and this "weathering" will have *destroyed* older small craters. The thicker debris layer and the much smaller frequency of large craters may account for the smoothness of the planet as derived from its radar returns.

8. *Expected Program of Surface Interpretation*

Because of the numerous close parallels between the Mercury surface and that of the Moon, cited above, some forecasts can be made regarding the stages of exploration which will follow the acquisition of pictures with 1 km or better resolution. This kind of resolution resembles modern telescopic resolution of the Moon, so that the history of lunar exploration might, in some measure, be repeated for Mercury.

Telescopic observation of the Moon, visual and photographic, sufficed for arriving at the modern interpretation of the lunar maria, including their approximate ages of the flooding (Kuiper 1954 and 1959) and the recognition of overlapping lava flows, most clearly observed on Mare Imbrium. The lunar maria were found to belong to two classes: impact maria which partially or nearly completely flooded with endogenic lavas (not caused by the impact but supplied from the interior); and flooded low lands, not obviously caused by impacts. The lunar impact maria are surrounded by mountainous walls (Baldwin 1949). Further studies disclosed that additional concentric mountain rings are often present, forming roughly geometric progressions in radii (Hartmann and Kuiper 1962). It was further found that the times of flooding were delayed with respect to the impacts causing the basins, by thousands or possibly hundreds of thousands of years, different for different basins. This was shown by the numbers of fairly large impact craters formed on the inside sloping walls of the basins before the flooding occurred.

The lunar craters fall into three broad categories: early pre-mare, with no central peaks; late pre-mare, with central peaks whose volumes depend upon the depth of the crater floor; and post-mare, with whitish, small, multiple central peaks. The central mountains appear igneous in nature. This sequence of events appears to be the direct result of the timing of the impact with respect to the period of maximum melting on the Moon (Kuiper 1954). Related to this is the isostatic adjustment of pre-mare crater floors from the original concave to convex, clearly the result of subsurface melting.

A number of important discoveries regarding the lunar surface were made during the past decade, after: (1) 3 orders of magnitude in resolution were gained during the Ranger VII, VIII, and IX missions; (2) another 2-3 orders of magnitude from the pictures returned by the soft-landers (Surveyor and Luna 9); and direct tests of the bearing strength of the surface became possible as well as direct chemical analyses from α-scattering experiments, showing that the lunar maria were indeed essentially basaltic in composition, as inferred from telescopic observations; (3) the entire lunar surface was recorded with moderate- to high-resolution by the Orbiter series; and (4) when the climax was achieved in 1969 by manned landings and the return to Earth of lunar surface materials, with the resulting enormously-expanded information on isotope chemistry, trapped gases, ages, and the structure of lunar rocks and surface debris (*Science* 1970).

Considering the possibility of 0.1-1 km resolution for Mercury, only the lunar Ranger and Orbiter records need to be considered for comparison in addition to Earth-based photography (resolution 300 meters). The Ranger records demonstrated the existence of extremely numerous collapse depressions in lunar lava fields (size range mostly 30-500 meters, with some depressions, e.g., on the floors of Ptolemaeus and Hipparchus even larger and visible telescopically). Also discovered by Ranger were the first lunar rocks, up to a few meters in diameter, and allowing a determination of an average bearing strength of the upper ½ meter of the lunar surface (approximately 1 kg/cm^2; Kuiper, Storm, Le Poole 1966). The Ranger records showed that the lunar grid system was traceable to the meter scale which meant that the thickness of the debris layer was of the order of 1 meter. The Orbiter records added much information on lunar rilles substantiating conclusions from ground-based observations that the sinuous rilles are old lava channels (Strom 1966). Also, the Orbiter records for the first time clearly demonstrated the existence and extent of induced volcanism resulting from the Tycho impact, with numerous lava lakes and lava flows found on the outer slopes of a crater that by all accounts is comparatively recent. Earth-based photography of the Moon at full phase sufficed to show sharply bounded color provinces (Whitaker 1965) which in several cases could be interpreted as due to discrete lava flows. A similar approach is likely to be productive for the planet Mercury.

Mercury observed with 0.1-1 km resolution would give quite satisfactory outlines of the maria and of the highlands between, but will probably not show rocks. It would be interesting to discover whether on Mercury any true impact mare exists, with near-circular mountain walls. The answer may well be negative, with only flooded maria present, as Mare Nubium on the Moon (and presumably most of the maria on Mars); because the impact maria on the Moon are almost certainly due to circumterrestrial bodies, not small asteroids (Kuiper 1954), which struck the Moon with high frequency during a

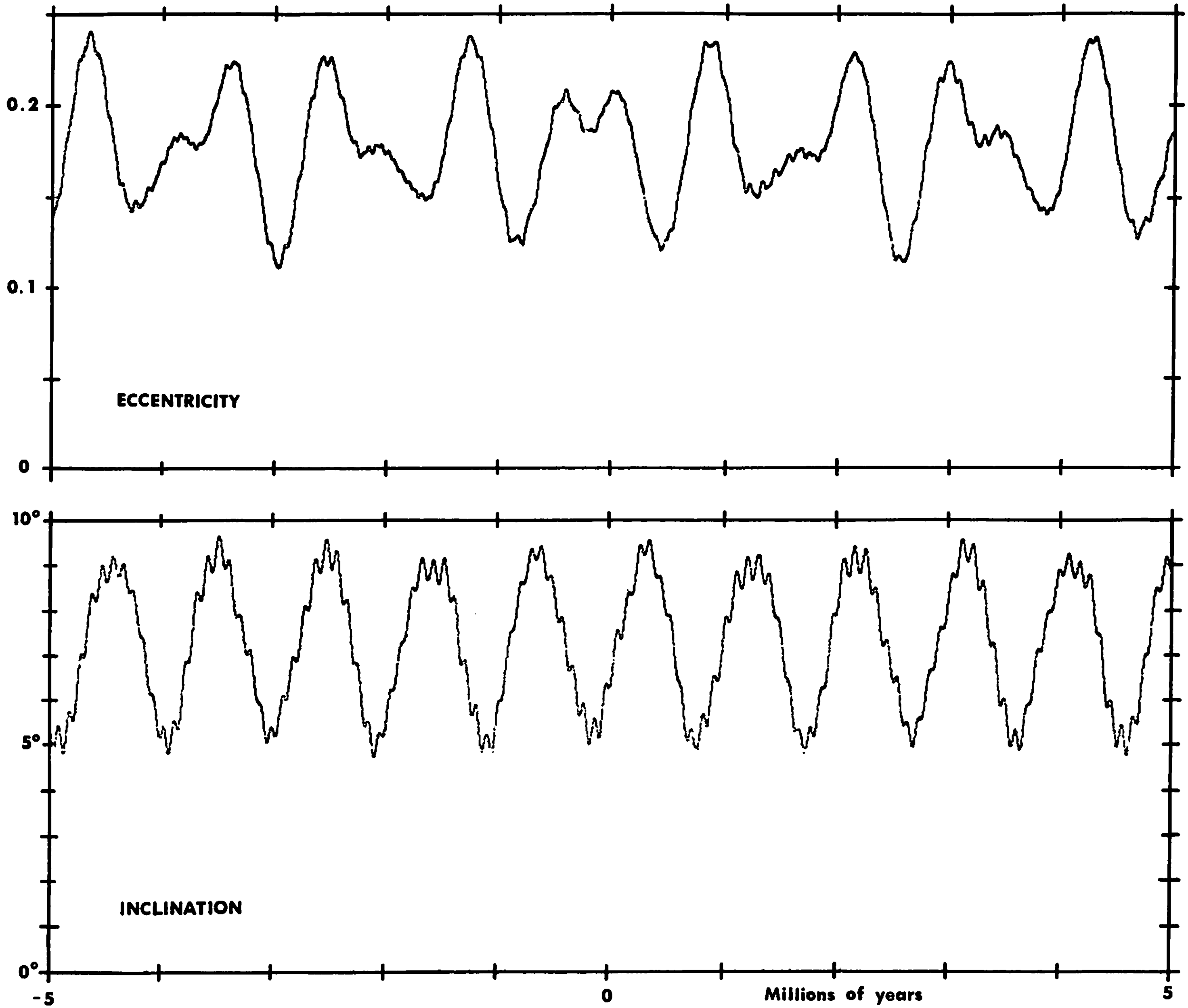

Fig. 5 Time variation of orbital eccentricity and inclination of Mercury (with respect to invariable plane) for 10,000,000 years centered on present (courtesy Hubbard, Oesterwinter, and Cohen, in press).

very limited period of time, roughly coincident with the period of maximum melting. Both the frequency- and size-distributions of craters will be of interest, with the frequency expected to be far below that on the lunar maria, and with the cometary/asteroidal impact ratio quite different from the Moon or Mars. Rilles or graben may be present as on lunar maria, inside and roughly parallel to the shore lines. A grid system on Mercury would be expected only if the original rotation of the planet were much faster. There may be some evidence for "weathering" by subsequent impacts and temperature variations, but with 1-km resolution these effects may not be conspicuous since there will be no aeolian deposits as on Mars. A few large ray craters of the Tycho or Copernicus type and more smaller ones may be present, unless a rapid surface turnover by micrometeorites would obliterate the rays themselves in 10^8-10^9 years or less. Evidence from the light-colored areas for a period of high surface temperature would be of extraordinary interest. Major mountain systems not related to the maria are not expected for a body, not much larger than the Moon, on which continent formation has probably not occurred; nor may there be much evidence of volcanism other than directly associated with the original mare deposits and high-velocity impact craters (such as Tycho). However, Mercury may present great surprises.

Not discussed here are interactions between the planet and the solar wind and with extreme short-wave solar radiations. These problems are almost independent from those related to pictorial records (though not quite of the planet's albedo, color, and polarization). The Mercury-solar interactions will much depend on the strength of the planetary magnetic field, as yet unknown, but presumably small because of the planet's slow rotation. The corresponding lunar problems may again guide the Mercury studies rather than the immensely more complex phenomena associated with the Earth (summarized, e.g., by Friedman and Johnson 1970).

APPENDIX

Through the courtesy of Drs. E. C. Hubbard, C. Oesterwinter, and C. J. Cohen, we are able to reproduce in Fig. 5 two plots, showing the variation of the orbital eccentricity and inclination (with respect to the invariable plane of the solar system) for a period 10^7 years centered on the present. These plots are based on the theory by Brouwer and van Woerkom, "The Secular Variations of the Orbital Elements of the Principal Planets," *Astron. Papers,* Vol. XIII, Part II, 1950, and will be published with similar plots for the other planets in their new journal, *Celestial Mechanics.* They comment that Mercury's total variation of *e*, according to this plot, is from 0.239 to 0.110 as against 0.241 and 0.109, quoted in our text from Brouwer and Clemence.

REFERENCES

Anders, E., and Arnold, J. R. 1965, "Age of Craters on Mars," *Science,* **149**, 1494–1496.

Anders, E. 1968 "Chemical Processes in the Early Solar System as Inferred from Meteorites," *Account. Chem. Res.,* **1**, 289–298.

Arnold, J. R. 1964, "The Origin of Meteorites as Small Bodies," in *Isotopic and Cosmic Chemistry* (Amsterdam: North-Holland Pub. Co.), Chap. 23.

Ash, M. E., Shapiro, I. I., and Smith, W. B. 1967, "Astronomical Constants and Planetary Ephemerides Deduced from Radar and Optical Observations," *A.J.,* **72**, 338–350.

Baldwin, R. B. 1949, *The Face of the Moon* (Chicago: Univ. of Chicago Press).

Belton, M. J. S., Hunten, D. M., and McElroy, M. B. 1967, "A Search for an Atmosphere on Mercury," *Ap. J.,* **150**, 1111–1124.

Bergstralh, J. T., Gray, L. D. and Smith, H. J. 1967, "An Upper Limit for Atmospheric Carbon Dioxide on Mercury," *Ap. J.,* **149**, L137–L139.

Binder, A. B. and Cruikshank, D. P. 1967, "Mercury: New Observations in the Infrared Bands of Carbon Dioxide," *Science,* **155**, 1135.

Brouwer, D. and Clemence, G. M. 1961, "Orbits and Masses of Planets and Satellites," in *Planets and Satellites: The Solar System* (Chicago: Univ. of Chicago Press), **III**.

Brouwer, D. and van Woerkom, A. J. J. 1950, "The Secular Variations of the Orbital Elements of the Principal Planets," Astronomical Papers, *American Ephemeris and Nautical Almanac,* **XIII**, Part II, pp. 81–107.

Camichel, H. and Dollfus, A. 1968, "La Rotation et la Cartographie de la Planete Mercure," *Icarus,* 8, 216–226.

Colombo, G. 1965, "Rotational Period of the Planet Mercury," *Nature,* **208**, 575.

Colombo, G. and Shapiro, I. I. 1965, "The Rotation of the Planet Mercury," Smithsonian Astrophysical Obs. Special Report 188R (also in *Ap. J.,* **145**, 296–307, 1966).

Friedman, H. and Johnson, F. S. 1970, "A Decade of Discovery," *Trans. Amer. Geophys. Union,* **51**, No. 1, pp. 4–8.

Goldreich, P. and Peale, S. J. 1966, "Resonant Spin States in the Solar System," *Nature,* **209**, 1078–1079.

Harris, D. L. 1961, "Photometry and Colorimetry of Planets and Satellites," in *The Solar System* (Chicago: Univ. of Chicago Press), **III**, Chap. 8.

Harris, P. G. and Tozer, D. C. 1967, "Fractionation of Iron in the Solar System," *Nature,* **215**, 1449–1451.

Hartmann, W. K. and Kuiper, G. P. 1962, "Concentric Structures Surrounding Lunar Basins," *Comm. LPL* No. 12, **1**, 51–56.

Hayashi, C. 1966, "Evolution of Protostars," *Ann. Rev. Astr. Ap.,* 4, 171–192.

Hodge, P. W. 1964, "The Atmosphere of the Planet Mercury," *Trans. Amer. Geophys. Union,* **45**, 631.

Irvine, W. M., Simon, T., Menzel, D. H., Pikoos, C., and Young, A. T. 1968, "Multicolor Photoelectric Photometry of the Brighter Planets. III. Observations from Boyden Observatory," *A.J.,* 73, 807–828.

Kaula, W. M. 1968, *An Introduction to Planetary Physics: The Terrestrial Planets* (New York: John Wiley and Sons, Inc.)

Kuiper, G. P. 1954, "On the Origin of the Lunar Surface Features," *Proc. Nat. Acad. Sci.,* **40**, 1096–1112.

Kuiper, G. P. 1957, "Visual Observations of Mars," *Ap. J.,* **125**, 307–317.

Kuiper, G. P. 1959, "Exploration of the Moon," in *Vistas in Astronautics,* **II**, 273–312.

Kuiper, G. P. 1965, "Interpretation of *Ranger VII* Records. Part 2," in *Experimenters' Analyses and Interpretations,* (JPL TR 32–700), pp. 9–73.

Kuiper, G. P., Strom, R. G. and Le Poole, R. S. 1966, "Interpretation of *Ranger VIII* and *IX* Records. Part 2," *Experimenters' Analyses and Interpretations,* (JPL TR 32–800), pp. 35–248.

Kuiper, G. P., Cruikshank, D. P. and Fink, U. 1970, Preliminary report presented at CalTech/JPL Mercury Symposium on Feb. 4, 1970, based on interferometric spectra obtained at Catalina Obs., December 1969 (resolution 5 cm^{-1}).

Lyot, B. 1929, *Ann. Obs. Meudon,* 8. Results sumarized by A. Dollfus, *The Solar System,* **III**, Chap. 9, p. 368; cf. also pp. 371–373 for Dollfus' own observations.

Moroz, V. I. 1965, "Infrared Spectrum of Mercury (λ 1.0–3.9 μ)," *Sov. Astr.,* 8, 882–889.

Muhleman, D. O. 1969, "On the Radio Method of Determining the Astronomical Unit," *M.N.R.A.S.,* 144, 155–157.

Mulholland, J. D. 1968, "Precession Effects of New Planetary Masses Used in JPL Ephemeris Development," in *Abstracts,* American Astronomical Society Meeting, August 20–23, 1968, p. 40. Also see *A.J.,* 73, p. S194, 1968.

Newcomb, S. 1895, "The Elements of the Four Inner Planets and the Fundamental Constants of Astronomy," in *Supplement to the American Emphemeris and Nautical Almanac for 1897.*

O'Leary, B. T., and Rea, D. G. 1967, "On the Polarimetric Evidence for an Atmosphere on Mercury," *Ap. J.,* 148, 249–253.

Öpik, E. J. 1951, *Proc. R. Irish Acad.,* 54A, pp. 165–199, reissued as *Armagh Obs. Contri.* No. 6; also see *Advan. Astron. Astrophys.,* **2**, 219–261, 1963.

Öpik, E. J. 1960, "The Lunar Surface as an Impact Counter," *M.N.R.A.S.,* 120, 404–411.

Peale, S. J. and Gold, T. 1965, "Rotation of the Planet Mercury," *Nature,* **206**, 1240–1241.

Pettengill, G. H. and Dyce, K. 1965, "A Radar Determination of the Rotation of the Planet Mercury," *Nature,* **206**, 1240.

Pettengill, G. H., Dyce, R. B. and Campbell, D. B. 1967, "Radar Measurements at 70 cm of Venus and Mercury," *A.J.,* **72**, 330–337.

Rabe, E. 1950, "Derivations of Fundamental Astronomical Constants from the Observations of Eros During 1926–1945," *A.J.,* **55**, 112–126.

Science, 30 Jan 1970 (The Moon Issue), **167**, No. 3918.

Shapiro, I. I. 1967, "Planetary Radar Astronomy," in *Moon and Planets,* ed. A. Dollfus (Amsterdam: North-Holland Pub.), p. 111.

Schiaparelli, G. 1890, "Sulla Rotazione di Mercurio," *A.N.,* **123**, 242–250.

Strom, R. G. 1966, "Interpretation of *Ranger VIII* and *IV* Records. Part 2," in *Experimenters' Analyses and Interpretations,* (JPL TR 32–800), pp. 199–210.

Whitaker, E. A. 1965, "Interpretation of *Ranger VII* Records. Part 2," in *Experimenters' Analysis and Interpretations,* (JPL TR 32–700), pp. 26–32.

Witting, J., Narin, F. and Stone, C. A. 1965, "Mars: Age of Its Craters," *Science,* **149**, 1496–1498.