tional Aeronautics and Space Administration Special Paper, Washington, D.C., in press).
4. T. B. McCord, M. P. Charette, T. V. Johnson, L. A. Lebofsky, C. Pieters, *Moon* **5**, 52 (1972).
5. C. Pieters, T. B. McCord, J. B. Adams, S. H. Zisk, *J. Geophys. Res.* **78**, 5867 (1973).
6. M. P. Charette, T. B. McCord, C. Pieters, J. B. Adams, *ibid.*, in press.
7. T. B. McCord and J. B. Adams, *Moon* **7**, 453 (1973).
8. J. B. Adams and T. B. McCord, *Science* **171**, 567 (1971); *Geochim. Cosmochim. Acta* **35** (Suppl. 2), 2183 (1971).
9. ———, *Geochim. Cosmochim. Acta* **36** (Suppl. 3), 3021 (1972).
10. Sample numbers: 70017.52, 72141.5, 72161.1, 72500.5, 72701.11, 73121.3, 73241.2, 73261.5, 73281.3, 74001.1, 74121.1, 74220.55, 74241.31, 75080.5, 75081.34, 75111.1, 75121.1, 76240.7, 76261.11, 78121.1, 78155.29, 78481.14, 78501.11, 79221.13, and 79511.1. J. B. Adams and T. B. McCord, *Geochim. Cosmochim. Acta* **34** (Suppl. 1), 1937 (1970).
11. T. B. McCord, M. P. Charette, T. V. Johnson, L. A. Lebofsky, C. Pieters, J. B. Adams, *J. Geophys. Res.* **77**, 1349 (1972).
12. T. B. McCord, *ibid.* **74**, 3131 (1969).
13. J. M. Rhodes, *Trans. Am. Geophys. Union* **54**, 609 (1973) (abstr.); S. Ghose, F. P. Okamura, J. S. Nelson, I. S. McCallum, *ibid.*, p. 588 (abstr.); S. J. Kridelbaugh, *ibid.*, p. 597 (abstr.); O. A. Schaeffer and L. Husain, *ibid.*, p. 614 (abstr.).
14. Apollo 17 Preliminary Examination Team, *Science* **182**, 659 (1973).
15. G. H. Heiken and D. S. McKay, paper presented at the Geological Society of America annual meeting, Dallas, November 1973; D. S. McKay and G. H. Heiken, *Trans. Am. Geophys. Union* **54**, 599 (1973) (abstr.).
16. J. E. Conel and D. B. Nash, *Geochim. Cosmochim. Acta* **34** (Suppl. 1), 2013 (1970); P. M. Bell and H. K. Mao, *ibid.* **36** (Suppl. 3), 545 (1972); R. G. Burns, R. M. Abu-Eid, F. E. Huggins, *ibid.*, p. 533; H. K. Mao, D. Virgo, P. M. Bell, *Trans. Am. Geophys. Union* **54**, 598 (1973) (abstr.).
17. W. R. Muehlberger *et al.*, "Interagency Report: Astrogeology 71" (U.S. Geological Survey, Washington, D.C., 1973); W. R. Muehlberger *et al.*, in *Apollo 17 Preliminary Science Report* (National Aeronautics and Space Administration Special Paper, Washington, D.C., in press).
18. Samples from the North and South Massifs, the sculptured hills, and the light mantle have also been analyzed by our group. Although they are spectrally distinct from the units described here, a detailed discussion is beyond the scope of this report.
19. T. B. McCord and J. A. Westphal, *Appl. Opt.* **11**, 522 (1972); T. B. McCord and J. Bosel, in *Astronomical Observations with Television Type Sensors*, J. W. Glaspey and G. A. H. Walker, Eds. (Univ. of British Columbia Press, Vancouver, 1973), p. 137.
20. T. B. McCord, thesis, California Institute of Technology (1968); "MITPAL [MIT Planetary Astronomy Laboratory] Lunar Spectral Reflectivity Atlas" (unpublished) (Department of Earth and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, 1972); E. A. Whitaker, *Moon* **4**, 348 (1972).
21. This research was supported by NASA grants NGL 22-009-350, NGL 31-006-011, and NGR 22-009-790. Publication No. 90 from the Planetary Astronomy Laboratory, Massachusetts Institute of Technology.
* Visiting Astronomer, Kitt Peak National Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

21 August 1973; revised 26 November 1973

Polarized Magnetic Field Fluctuations at the Apollo 15 Site: Possible Regional Influence on Lunar Induction

Abstract. *High-frequency (5 to 40 millihertz) induced lunar magnetic fields, observed at the Apollo 15 site near the southeastern boundary of Mare Imbrium and the southwestern boundary of Mare Serenitatis, show a strong tendency toward linear polarization in a direction radial to the Imbrium basin and circumferential to the Serenitatis basin, a property that could be indicative of a possible regional influence on the induction.*

Time-dependent magnetic fields recorded by the lunar surface magnetometer (LSM) at the Apollo 15 site (~ 26°6′N, 3°39′E) near Hadley Rille on the southeastern margin of Mare Imbrium show a noteworthy response to electromagnetic induction by variations in the interplanetary magnetic field. Above approximately 5 mhz, magnetic field oscillations at the LSM are strongly linearly polarized in a direction roughly northwest-southeast and tangent to the lunar surface at the Apollo 15 site. This direction is approximately radial with respect to the circular Imbrium basin and is also approximately parallel to Montes Haemus, forming the southwestern boundary of Mare Serenitatis. The local steady magnetic field at the Apollo 15 site is small [3.3 ± 1.5, 0.9 ± 2.0, and 0.2 ± 1.5 gammas in the vertical, easterly, and southerly directions, respectively (*1*)], thus bearing no obvious relationship to the phenomenon. In a brief report of the Apollo 15 lunar inductive response Smith *et al.* (*2*) did not consider polarization effects. We speculate that these linearly polarized magnetic field oscillations oriented along a northwest-southeast line may be a regional inductive response to interplanetary field variations, associated with the close proximity of either the Imbrium basin or the Serenitatis basin, or both.

Striking evidence for the almost invariant orientation of magnetic field oscillations seen by the LSM is the mirror-image symmetry of the time series of magnetic field fluctuations in the plane tangent to the surface and in the eastward and northward directions at the Apollo 15 site, B_y and B_z, respectively. Three separate 30-minute time swaths shown in Fig. 1 display obvious mirror-imaging, resulting from the east-west, north-south decomposition of strongly linearly polarized magnetic field fluctuations oriented northwest-southeast. During the half-hour intervals shown in Fig. 1, the moon was in the solar wind and the LSM was located just beyond the dusk limb on the nightside. Time series records of magnetic field oscillations observed by the Ames magnetometer on the Explorer 35 (Ex 35) satellite in lunar orbit, during the identical time intervals used in Fig. 1, showed no evidence of a similar preferred polarization. The Ex 35 magnetometer measures the interplanetary magnetic fields driving the lunar inductive response. Thus, either the global induction somehow introduces a preferred northwest-southeast polarization from the field of interplanetary polarizations whose only preferred direction is north-south [this report and (*3*)], or the induction is dominated locally by spatial variations in physical properties which cause eddy currents to flow in preferred directions.

For a more quantitative study of the Apollo 15 magnetic field oscillations, we have carried out Fourier analyses of the time series records of the instrument during its first lunation of operation. Power spectral densities have also been computed for simultaneous Ex 35 magnetic field data. The data reduction techniques are identical to those used in the analyses of the Apollo 12 LSM data (*4*). Figure 2, A and B, shows the directional properties of the power spectral density (in gammas squared per hertz) of the fluctuations in the magnetic field tangent to the lunar surface at the Apollo 15 site for frequencies of 1.66, 4.97, 7.45, 9.94, 19.9, and 39.7 mhz. Directional characteristics of the power spectral density of the interplanetary magnetic field oscillations projected on the plane locally tangent at the Apollo 15 site are also shown in Fig. 2 (Ex 35). In the polar plots of Fig. 2, 0°, 90°, 180°, and 270° are local east, north, west, and south, respectively, at the Apollo 15 site, and in any particular direction the length of the vector is proportional to the power spectral density. The data used in Fig. 2 were obtained when the LSM was in daylight, exposed to the solar wind. Local times were approximately midmorning and midafternoon for Fig. 2, A and B, respectively.

The power at the LSM and at Ex 35 have qualitatively similar directional behavior below about 5 mhz. At these frequencies the Apollo 15 magnetic fields appear to reflect the global lunar response to electromagnetic induction already observed on the Apollo 12 mission (*2, 4–6*). In the case of Fig. 2A, at 1.66 and 4.97 mhz, the interplanetary power (Ex 35) has a strong maximum 10° to 20° east of north, whereas for Fig. 2B maximum power is found in the north-south orientation at the lowest frequency and roughly N20°W at 4.97 mhz. These directions are in agreement with the observations of Belcher and Davis (*3*), who found that interplanetary magnetic field fluctuations were predominantly normal to the ecliptic plane. Most importantly, for these lower frequencies the directional properties of the power at the LSM and at Ex 35 are approximately the same. Small differences in directional properties can be understood in terms of changes in the plane of polarization of electromagnetic plane waves upon scattering from the moon and its diamagnetic cavity (*7*). The power at the LSM is amplified with respect to the Ex 35 power by the solar wind compression of induced lunar magnetic fields (*2, 4, 5*).

As can be seen in Fig. 2, at 7.45 mhz and at higher frequencies, a dramatic change occurs in the directional properties of the LSM power relative to the Ex 35 power. In Fig. 2A the Ex 35 power maximizes about 20° to 40° east of north; however, the LSM power no longer tracks Ex 35 but shifts to a maximum 20° to 30° north of west. In Fig. 2B, the direction of maximum Ex 35 power is more variable at these higher frequencies, changing from about N30°W to about N20°E. Nonetheless, the direction of maximum LSM power is always 40° to 60° west of north. The directional power of magnetic field fluctuations at the Apollo 15 site, at frequencies above about 5 mhz, is invariably a maximum approximately northwest-southeast, independent of the directional character of the interplanetary power.

The cases shown in Fig. 2 are two of 24 Apollo 15 LSM daylight time series data swaths so far analyzed. At the highest frequencies, 19.9 and 39.7 mhz, the maximum LSM power is between 20° and 60° north of west in all 24 cases, whereas the directions of the Ex 35 power maxima vary widely. At 9.94 mhz the maximum LSM power is 20° to 60° north of west in 20 of 24 cases (in three cases the directions are between 60° and 80° north of west and in one case it is 0° to 20° south of west), whereas the directions of the maximum Ex 35 power are again widely spread, showing a slight preference for 10° to 30° east of north. For 7.45 mhz the distribution of directions of maximum power at the LSM is essentially identical to that at 9.94 mhz. At 4.97 mhz there is a small preference for the LSM direction of maximum power to lie 40° to 80° north of west, whereas at 1.66 mhz the directional properties of the LSM and Ex 35 power are nearly identical.

Figure 2 and the supporting data show that at frequencies above about 5 mhz magnetic field oscillations at the Apollo 15 site are very strongly polarized in approximately the northwest-southeast line, independent of the polarization of the interplanetary magnetic field. This phenomenon manifests itself quite abruptly in frequency; below about 5 mhz, the polarization of the LSM measured magnetic fields reflects essentially that of the Ex 35 measured fields. A preliminary assessment of additional lunations of Apollo 15 LSM data indicates that this strong polarization of signals is also characteristic of the additional data (*8*).

We have investigated the possibility that this polarization property results from global electromagnetic induction in a moon with spherically symmetric electric and magnetic properties (*7*), and, although we can understand how the plane of polarization of a wave can be rotated by scattering from the

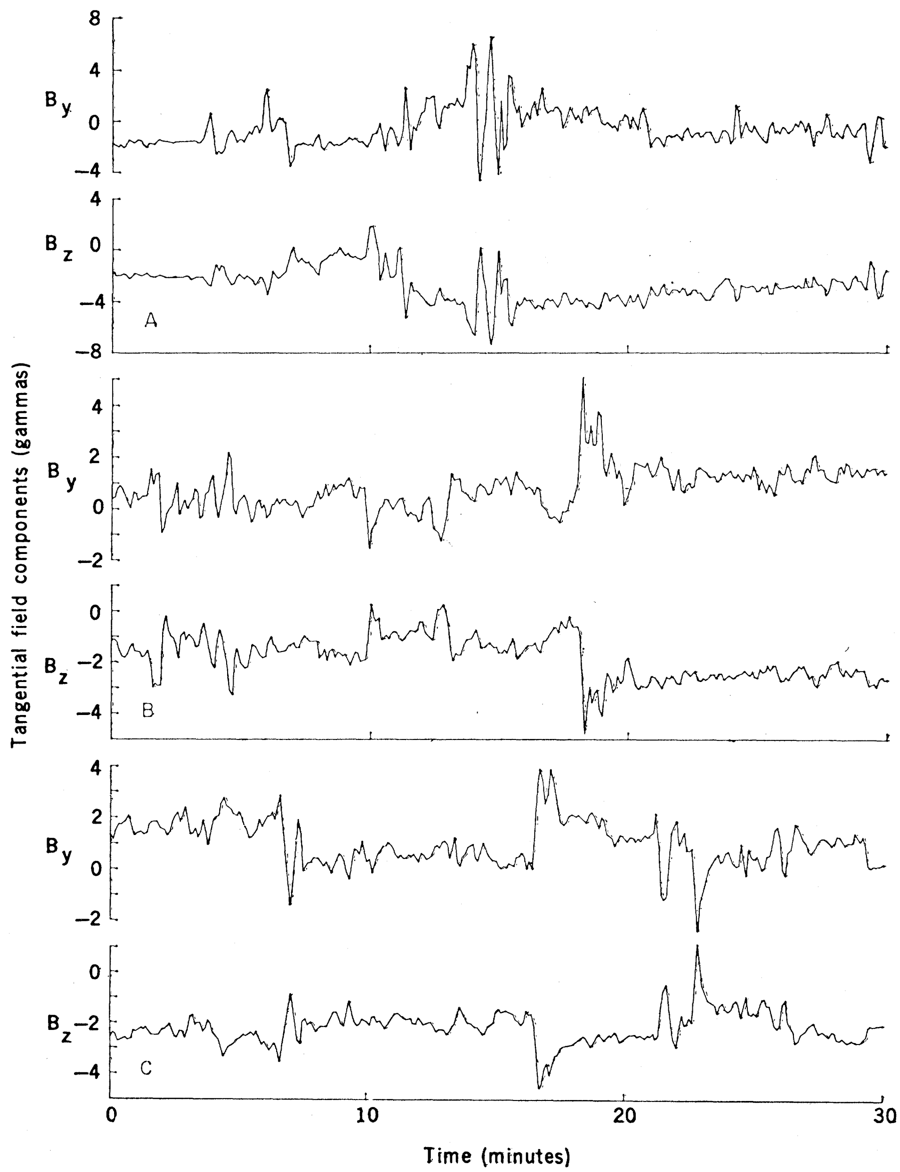

Fig. 1. Mirror-image symmetry in three separate time series swaths (A–C) of magnetic field fluctuations in the plane tangent to the surface and in the eastward and northward directions at the Apollo 15 site, B_y and B_z, respectively. The mirror-imaging results from the east-west, north-south decomposition of strongly linearly polarized magnetic field fluctuations oriented northwest-southeast.

moon and its diamagnetic cavity, it is not presently clear how a field of waves with polarization planes symmetrically distributed about a north-south line (as is the case for the interplanetary field) can be preferentially rotated to another direction. Perhaps if the lunar excitation is mainly due to Alfvén waves traveling along the mean magnetic field spiral direction, an asymmetry would be introduced, via interaction of these waves with the moon and its downstream plasma void, sufficient to account for the observations. Other possible explanations for the polarization of the Apollo 15 signals include a global, that is, nearside versus farside, asymmetry in the lunar electric and magnetic properties or a more regional asymmetry. The proximity of the Apollo 15 site to the Imbrium and Serenitatis basins and the approximate coincidence of the polarization direction with the direction to the center of Mare Imbrium and the direction circumferential to Mare Serenitatis are suggestive of a reigonal influence on the Apollo 15 LSM response. For example, if these mascons contain disk-like layers (*9*) with electric and magnetic properties different from those of their surroundings, induction currents might flow preferentially circumferentially along the edge of the disk, producing radially oriented induced magnetic fields. Deep faults concentric with an impact basin might also tend to confine induction currents to be circumferential.

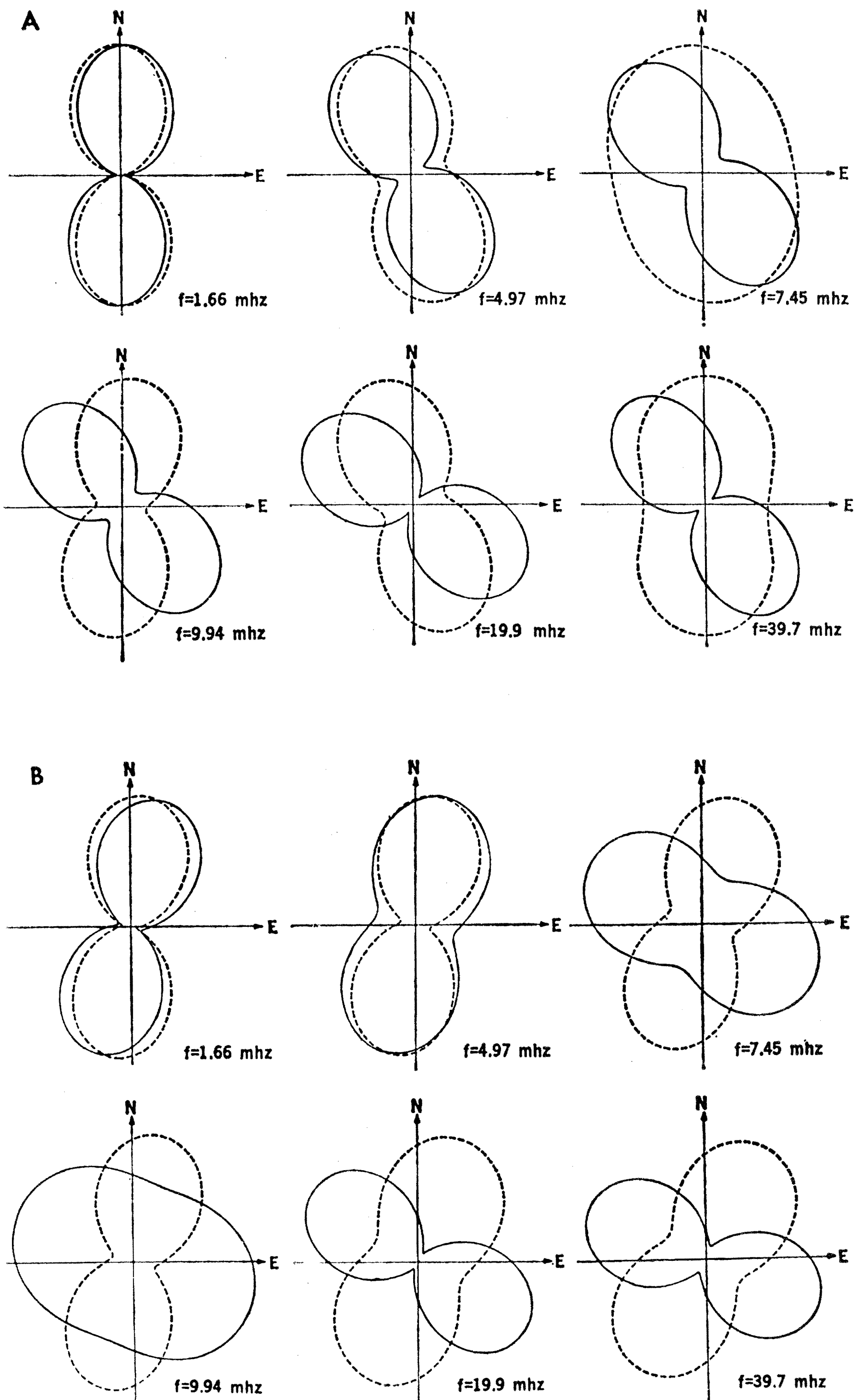

Fig. 2. Polar plots of power spectral density (in gammas squared per hertz) of the magnetic field fluctuations measured by the LSM and Ex 35 and tangent to the lunar surface at the Apollo 15 site for frequencies of 1.66, 4.97, 7.45, 9.94, 19.9, and 39.7 mhz. Local east is 0° and local north is 90°. During these periods, the moon was in the solar wind and local time at LSM was either midmorning (A) or midafternoon (B). (Solid curves) Apollo 15 LSM; (dashed curves) Ex 35.

Finally we note that the polarization observed by Apollo 15 may be related to a less distinctive directional asymmetry observed in the Apollo 12 LSM power which tends to a maximum some 10° to 30° west of north, whereas the corresponding Ex 35 power maximizes along a north-south line. The relatively stronger local remanent magnetic field at the Apollo 12 site (~ 3°11′S, 23°23′W) is oriented in about the same direction as the maximum in LSM inductive power. We have hitherto interpreted this coincidence as implying some effect of the local field on the observed induction (*4*); however, the Apollo 15 LSM data suggest that perhaps the Apollo 12 LSM has observed a weaker regional influence of the Imbrium and Serenitatis structures lying relatively far to the north, or that a combination of the two effects is present at the Apollo 12 site.

G. Schubert
Department of Planetary and Space Science, University of California, Los Angeles 90024

B. F. Smith
NASA Ames Research Center, Moffett Field, California 94035

C. P. Sonett
Department of Planetary Sciences and *Lunar and Planetary Laboratory, University of Arizona, Tucson 85721*

D. S. Colburn
NASA Ames Research Center

K. Schwartz*
5160 Camino Floral, Santa Barbara, California 93111

References and Notes

1. P. Dyal, C. W. Parkin, W. Daily, in *Proceedings of the Fourth Lunar Science Conference* (Pergamon, Elmsford, N.Y., 1973), vol. 3, pp. 2925–2945.
2. B. F. Smith, G. Schubert, D. S. Colburn, C. P. Sonett, K. Schwartz, in *Lunar Science IV*, J. W. Chamberlain and C. Watkins, Eds. (Lunar Science Institute, Houston, 1973), pp. 683–685.
3. J. W. Belcher and L. Davis, Jr., *J. Geophys. Res.* **76**, 3534 (1971).
4. C. P. Sonett, D. S. Colburn, P. Dyal, C. W. Parkin, B. F. Smith, G. Schubert, K. Schwartz, *Nature (Lond.)* **230**, 359 (1971); C. P. Sonett, G. Schubert, B. F. Smith, K. Schwartz, D. S. Colburn, in *Proceedings of the Second Lunar Science Conference*, A. A. Levinson, Ed. (MIT Press, Cambridge, Mass., 1971), vol. 3, pp. 2415–2431; C. P. Sonett, B. F. Smith, D. S. Colburn, G. Schubert, K. Schwartz, in *Proceedings of the Third Lunar Science Conference*, E. A. King, Jr., Ed. (MIT Press, Cambridge, Mass., 1972), vol. 3, pp. 2309–2336.
5. C. P. Sonett, P. Dyal, C. W. Parkin, D. S. Colburn, J. D. Mihalov, B. F. Smith, *Science* **172**, 256 (1971).
6. Not only are the directional properties of the Apollo 15 LSM and the Ex 35 power similar, but the magnitude of the Apollo 15 power relative to the Ex 35 power is in good agreement with the comparable power ratio for the Apollo 12 and Ex 35 instruments below about 5 mhz. Thus the lunar response at frequencies below about 5 mhz, as determined by both the Apollo 12 and Apollo 15 surface magnetometers, is essentially global, and the deep lunar electric conductivity, inferred by us (*4*) from these low-frequency measurements, is unaffected by the polarization phenomenon reported here.
7. Calculations are based on the electromagnetic scattering theory of K. Schwartz and G. Schubert [*J. Geophys. Res.* **78**, 6496 (1973)]; see also G. Schubert, K. Schwartz, C. P. Sonett, D. S. Colburn, B. F. Smith, in *Proceedings of the Fourth Lunar Science Conference* (Pergamon, Elmsford, N.Y., 1973), vol. 3, pp. 2909–2923; G. Schubert, C. P. Sonett, K. Schwartz, H. J. Lee, *J. Geophys. Res.* **78**, 2094 (1973); B. F. Smith, D. S. Colburn, G. Schubert, K. Schwartz, C. P. Sonett, *ibid.*, p. 5437.
8. This assessment is based on the observed coherence properties of Apollo 15 data in the instrument sensor coordinate system. Only between about midnight and dawn of the first lunation has the strongly polarized character of the LSM signals in the local tangential plane not been apparent.
9. The existence of mascons, or positive gravity anomalies associated with the circular mare basins such as Imbrium and Serenitatis, was discovered by P. M. Muller and W. L. Sjogren [*Science* **161**, 680 (1968)]. Recent work has shown that the best models for these mass concentrations are near-surface disks [see, for exam → W. L. Sjogren, P. Gottlieb, P. M. Muller, W. Wollenhaupt, *ibid.* **175**, 165 (1972)].
10. Supported in part under NASA contracts NAS9-13563 (C.P.S.) and NAS2-6876 (K.S.). G.S. was a Guggenheim Fellow during a portion of this investigation.
* Present address: General Electric–TEMPO, Santa Barbara, Calif. 93101.
26 October 1973; revised 10 December 1973 ■

Mercury: Does Its Atmosphere Contain Water?

Abstract. *The atmosphere of Mercury, like that of the moon, is maintained in an extremely tenuous minimum state by weak solar wind accretion and radioactive decay processes, and depleted by strong removal mechanisms. Unlike the moon, it has a high daytime surface temperature that promotes the production of water vapor, which may be the dominant atmospheric constituent derived from solar wind protons.*

Mercury's atmosphere is probably in a minimum state (10^{-10} mbar) which is maintained by solar wind accumulation and radioactive decay within the planet (*1*). It is destroyed by the loss mechanisms of gravitational escape, ion-sweeping by the solar wind electric field, and escape of suprathermal photodissociation fragments. These processes provide a quantitative understanding of the lunar atmosphere, as measured by instruments carried to the moon in the Apollo missions (*2*). Thus, a reasonable model for Mercury may be constructed, provided the scaling laws for the sources and losses are known. The details of such a model are being presented elsewhere (*3*). I suggest here an important difference that may exist between the moon and Mercury, namely that the primary proton-derived component of Mercury's atmosphere is H_2O, whereas for the moon it is probably H_2 (*4, 5*).

Since Mercury's dayside temperatures range between 100° and 325°C (*6*), chemical reactions of hydrogen with the oxygen in the soil can cause an outgassing of water vapor from the surface. This is a common occurrence in pyrolysis experiments on lunar samples (*7*). Although significant terrestrial water contamination is present, a major portion of the water is of solar wind origin (*8*). Apparently, energetic particle bombardment provides large numbers of dislocated oxygen atoms in the silicate lattice, which combine with hydrogen atoms to form OH and H_2O. This has been demonstrated experimentally by Cadenhead and Buergel (*9*), who show that molecular hydrogen is chemisorbed in outgassed lunar samples at 150°C and released as water vapor in the region 200° to 400°C.

Solar wind hydrogen is probably stored as H_2O in the outermost layers of lunar soil grains [to about 0.4 μm, according to Leich *et al.* (*10*)]. At lunar temperatures, the water is locked within the soil, and prolonged exposure to solar wind protons leads to H_2 production. It is probable that near the subsolar point, where the temperature reaches 100°C, some H_2O is given off (*5*). At Mercury's daytime temperatures, H_2O would be released as long as oxygen is available within the soil. The H_2O physisorbs on the cold night side (− 175°C). If the loss of suprathermal atomic hydrogen by photodissociation of H_2O exactly balanced the solar wind input, a balance of interchange of H_2O would occur between the atmosphere and the surface. (The OH and O photodissociation fragments are not energetic enough to escape, and ultimately recombine with hydrogen at the surface to reform H_2O.) However, loss of H_2O^+ ions from the atmosphere through solar wind sweeping would exhaust the oxygen within a few hundred years, were it not for various processes of erosion which tend to expose fresh surface. To maintain the oxygen supply to the atmosphere, an erosion rate R of at least 2 Å per year is needed. For $R > 650$ Å per year, the solar wind flux would not be sufficient to saturate the surface. In that case, the surface would act as a sink for solar wind and atmospheric hydrogen.

On the moon, erosive processes are of three types: solar wind sputtering, micrometeoroid impact, and gradual mixing of surface material by a number of poorly understood mechanisms. For a solar wind sputtering rate of 0.05 atom per incident atom (*11*), the solar wind removal rate is about 1 Å per year. This value is consistent with an estimate of 300 years for the time scale for removing the amorphous coating of the grains (*12*). Micrometeoroid removal rates of 10 Å per year are estimated by Neukem (*13*). Dust impact measurements from spacecraft indicate micrometeoroid fluxes of 2×10^{-9} g cm^{-2} year^{-1} (with a large uncertainty), which are capable of eroding 10 to 20 Å per year (*14*). Stirring of the soil inferred from cosmic-ray track ages imply effective values of $R > 40$ Å per year (*15*). Thus, sufficient stirring and scouring have occurred at the moon's distance, and it is reasonable to expect similar if not higher rates at the orbit of Mercury.

In summary, three regimes for Mercury's atmosphere can occur: (i) $R <$ 2 Å per year. The surface is fully reduced and the atmospheric hydrogen is in the form of H_2 with a mean surface density of 3.7×10^5 cm^{-3}. (ii) 2 Å per year $< R <$ 650 Å per