APOLLO 16

Preliminary Science Report

PREPARED BY

NASA MANNED SPACECRAFT CENTER

21. Lunar Orbital Mass Spectrometer Experiment

R. R. Hodges,[a] J. H. Hoffman,[a†] and D. E. Evans[b]

A lunar orbital mass spectrometer carried by the Apollo 16 command and service module (CSM) and a similar experiment carried on the Apollo 15 CSM were dedicated to the detection of lunar atmosphere and to a search for active lunar volcanism. Study of the lunar atmosphere obviously is important to understanding the evolution of the Moon. In addition, the tenuous atmosphere of the Moon is unique among accessible planets. Gas molecules do not collide with each other but, instead, travel in ballistic trajectories between encounters with the lunar surface to form a nearly classical exosphere, in which lateral transport can be observed in an idealized form. This study will aid in understanding transport mechanisms in other, more complex planetary exospheres.

The Apollo 14 and 15 cold cathode gages have provided an upper bound on the concentration of gases at the lunar surface of approximately 1×10^7 particles/cm^3 (ref. 21-1). This value has been shown by Hodges et al. (ref. 21-2) to imply that the upper bound on the average lunar volcanic release of gas is 1.5×10^{-16} g/cm^2/sec. Interestingly, this rate is only three or four orders of magnitude less than the degassing rate for the Earth, although the surface concentrations for the Earth and the Moon differ by more than 12 orders of magnitude. The difference in these ratios is attributable mainly to a shorter lifetime for lunar gases. It is important to note that the tenuous lunar atmosphere does not a priori imply a totally dead planet.

A persistent pattern of the Apollo 14 cold cathode gage data for 10 lunar days of operation can be seen in Johnson et al. (ref. 21-1) to be a daytime maximum more than an order of magnitude in excess of the nighttime concentration. This pattern suggests dominant gases that are adsorbed readily on the cold nighttime surface. Hodges and Johnson (ref. 21-3)

have shown that gases that are not adsorbed on the nighttime surface, such as neon (Ne), argon, and probably nitrogen, should be distributed roughly as the inverse 5/2 power of surface temperature and thus have nighttime maximums. The daytime maximum in the cold cathode gage data may be influenced by contaminant gases released from remnant spaceflight hardware, but the persistent level of this maximum suggests otherwise. If the daytime maximum is a natural feature of lunar atmosphere, then it results entirely from condensable volcanic gases, whereas the nighttime level represents the noncondensable gases, of which neon of solar wind origin is expected to dominate.

In lunar orbit (altitude ~100 km), the distribution of gases is influenced by the barometric law. Over the daytime side of the Moon, the scale height of neon (20 atomic mass units (amu)) is roughly 100 km, whereas that of argon (40 amu) is 50 km. Thus, in a 100-km orbit, the concentration differs from that at the surface by less than an order of magnitude for most gases; and, if the daytime maximum detected by the cold cathode gages is not artifact, it should be detected in orbit. A noncondensable gas, such as neon, should be approximately 30 times more abundant at the nighttime surface than in daytime (ref. 21-3). However, the night-to-day variation of scale height by a factor of nearly 4 compensates for this difference and results in very little variation along the orbit path (ref. 21-4).

Detection of active volcanism from lunar orbit requires the fortuitous passage of the spacecraft through a perturbation of lunar atmosphere over an active gas release. It is most likely that these events would be detected over the night side, where surface adsorption precludes multiple surface collisions and hence limits the lateral spreading of the perturbation to form a distinct disturbance that can be recognized in the mass spectrometer data. This problem has been analyzed by Hodges et al. (ref. 21-2). Evidence for one event has been found in the Apollo 15 data, but the certainty that it is not artifact has not yet been

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[a]The University of Texas at Dallas.

[b]NASA Manned Spacecraft Center.

[†]Principal Investigator.

established. Further study of all orbit data is needed before any definitive statement on active lunar volcanism can be made.

Details of the lunar orbital mass spectrometers have been presented by Hoffman et al. (refs. 21-5 and 21-6), and the calibration of the instruments is described by Yeager et al.[1] In this report, these facets are discussed in summary form, with emphasis on differences between the two flight instruments. Much of the Apollo 16 data analysis has been delayed, awaiting the availability of trajectory data. However, some significant results regarding the abundance of neon on the Moon have emerged from a preliminary study of fragmentary data.

EXPERIMENTAL PROCEDURE

The lunar orbital mass spectrometer (fig. 21-1) carried on the Apollo 16 CSM was similar to that carried on the Apollo 15 CSM. In flight, the instrument was mounted on a boom, which extended approximately 7.3 m from the CSM, with the opening of the inlet plenum facing the -X direction (that is, parallel to the roll axis and toward the service module (SM) end of the spacecraft). When the flight path was oriented so that the velocity vector was in the -X direction (SM forward), the gas inlet was in a ram
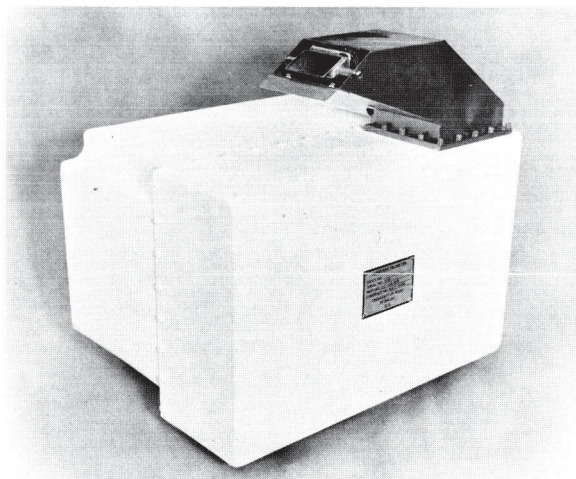

FIGURE 21-1.—Photograph of the lunar orbital mass spectrometer. The structure on the top of the instrument is the gas inlet plenum.

condition with respect to native gases of lunar atmosphere, whereas the reverse direction of flight (command module end forward) produced a wake condition at the inlet. This scheme was conceived to permit separation of data contributions from native gases and from spacecraft contaminants.

Data from the Apollo 15 experiment indicated that a large background of contaminant gases was present in lunar orbit but that these gases did not emanate directly from the spacecraft (refs. 21-5 and 21-6). The main source of the background was thought to be the vaporization of ice and other particles coorbiting with the CSM. Another suspected source was the release of adsorbed gases from the walls of the inlet plenum. To minimize the latter effect in the Apollo 16 experiment, the inlet structure was fitted with a thermally controlled inner plenum, which was heated to approximately $520°$ K to outgas for approximately 1 hr before operation of the experiment and then was held at $343°$ K during data collection.

The rest of the instrument has been described in detail previously by Hoffman et al. (refs. 21-5 and 21-6). The instrument consists of a magnetic sector-field analyzer with two ion collectors. One collector covers the mass range of 12 to 28 amu, whereas the other collector simultaneously sweeps through masses 28 to 67 amu. Ions of a given mass, when focused on one of the collectors, are counted for a period of 0.1 sec, after which the accumulated count is telemetered. Formation of ions at the junction of the gas inlet plenum and the analyzer is accomplished by an electron beam with energy of 70 eV. Sensitivity of this type of instrument is a function of ionization cross section of each gas species. To establish the absolute sensitivity factors for this instrument, the flight model was calibrated at the NASA Langley Research Center Molecular Beam Facility (MBF) as described by Yeager et al.[2] For most gases, one telemetered ion count corresponded to approximately 260 molecules/cm^3; but an important exception is neon, which is not easily ionized and for which one count corresponded to 1100 atoms/cm^3 in the lunar atmosphere. These numbers imply the capability to detect partial pressures in the range of

[1]P. Yeager, A. Smith, J. Jackson, and J. H. Hoffman: Absolute Calibration of Apollo Lunar Orbital Mass Spectrometer. To be published in J. Vac. Soc., 1972.

[2]Ibid.

1×10^{-14} torr (1×10^{-13} torr for neon), but unexpectedly high levels of contamination make the realization of this capability in data analysis quite difficult, as will be noted in subsequent discussion.

RESULTS

Analysis of the Apollo 16 data currently is in a preliminary stage, awaiting the availability of trajectory data. However, the examination of one segment of the data gives some interesting results on the pressure of ^{20}Ne on the Moon.

Shortly after the plane change and rendezvous of the Apollo 16 CSM and lunar module, the mass spectrometer detected the lowest levels of contamination yet found in lunar orbit. This state resulted in data in which very close scrutiny of the neon content of the lunar atmosphere can be made. A typical spectrum obtained on the lunar dark side at approximately 180:32 ground elapsed time (GET) is shown in figure 21-2. At that time, the spacecraft presumably was oriented with the -X-axis in the direction of the velocity vector so that the gas inlet of the mass spectrometer should have been collecting lunar gases. The dominant peak at mass 18 amu, which results from water, had an amplitude of approximately 1.75×10^4 ion counts per sample period (0.1 sec), which is well below the level at
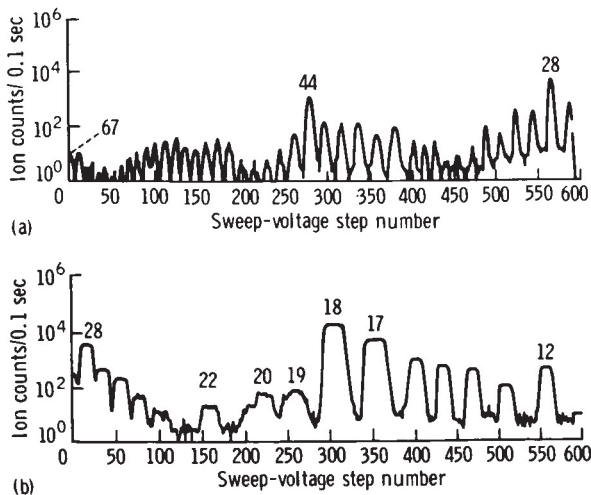

(a)

(b)

FIGURE 21-2.—Mass spectrum from Apollo 16 obtained at 180:32 GET over the dark side of the Moon. The horizontal scale gives the number of the data step corresponding to the sweep voltage that accelerates ions through the analyzer. (a) High mass range from 67 to 28 amu. (b) Low mass range from 28 to 12 amu.

which the counting system became nonlinear (at approximately 4×10^4 counts). Because of the high level of this peak on the dark side of the Moon, it is certain that the water vapor is mainly of spacecraft origin.

The dominance of water vapor in the mass spectrum has important effects on nearby peaks. For example, the 17-amu peak is attributable essentially to hydroxyl (OH) ions formed by fractionation of water molecules in the ion source. Because the water is terrestrial in origin, the abundance of $H_2^{18}O$ is 0.2 percent of that of $H_2^{16}O$, giving rise to 35 ± 1 counts at 20 amu at the time in question. A corresponding contribution of approximately 10 counts at 19 amu is attributable to ^{18}OH.

An expanded portion of the measured spectrum at 19 and 20 amu is shown in figure 21-3. Each data
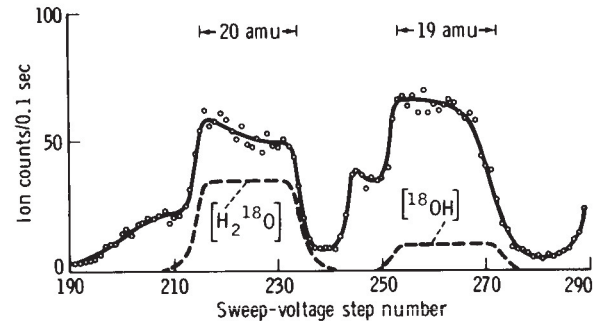

FIGURE 21-3.—Expanded portion of the low mass spectrum at 180:32 GET. Each data point represents the average of three measurements at the same sweep-voltage step number from three successive spectra. Contributions from $H_2^{18}O$ at 20 amu and ^{18}OH at 19 amu are indicated by dashed lines.

point is the average of three measurements at the indicated sweep-voltage step from three successive spectra. Dispersion of the data points about the fitted curve is in good agreement with the expected variance of an average of samples in a Poisson distribution of the ion count rate.

It can be noted in figure 21-3 that the 19- and 20-amu peaks do not have the nearly trapezoidal form that is typical of the low mass spectrum. Hence, rote subtraction of the 35-count contribution from $H_2^{18}O$ would not lead to a direct determination of the amount of the remaining gas at 20 amu, presumably ^{20}Ne. The only other 20-amu candidate is hydrogen fluoride, but its presence in lunar orbit is completely unexpected. Doubly ionized argon can be

ruled out because of the improbability of its presence as a contaminant or as a significant part of the nighttime lunar atmosphere at orbit altitude. (One count in the spectral data at 40 amu would imply approximately 1×10^6 atoms/cm^3 of argon at the surface.) The contribution of doubly ionized molecules of mass 40 amu probably is similar to that of other molecules, forming a fairly smooth background of multiply ionized gases with a level on the order of 1 count in the vicinity of the 20-amu peak.

The atypical shapes of the 19- and 20-amu peaks are the result of scatter of the intense $H_2^{16}O$ ion beam as it impinges on various protuberances, such as slit mounts, within the mass analyzer. Ion-molecule collisions contribute a nearly constant background of approximately 3 counts. In addition, at 19 amu, many hydrated protons (H_3O^+) are formed in collisions of water ions with water molecules. Because these hydrated ions are not formed in the electron beam of the ion source, they are not monoenergetic and thus contribute greatly to the distortion of the 19-amu peak.

To evaluate the actual amplitude of the 20-amu peak, it is necessary to understand the quantity of scattered water ions present. Inexact knowledge of the scattering process necessitates postulation of its behavior. It is assumed that scatter of ions from an obstacle would result in some thermal accommodation of the ions, giving rise to a nearly Gaussian spatial dispersion of the beam and, hence, of the resulting ion counts. This assumption has been applied to the rise in counts to the left of the 20-amu peak (sweep-voltage steps 190 to 211) and to the fall in counts at the top of the peak (sweep-voltage steps 216 to 232). A least-squares fit of these data to a uniform background, to a Gaussian distribution of scattered ions, and to an idealized, trapezoidal peak at 20 amu resulted in an amplitude of 46 counts for the trapezoidal-peak case. This result is illustrated in figure 21-4, in which the Gaussian distribution in question is labeled A and the background is 3 counts. The hump labeled B also results from scatter. The hump labeled C is the residual after subtraction of the 10 counts attributable to ^{18}OH known to be present. Hump C is caused by a combination of scatter of the water-ion beam and the H_3O^+ ions. Because the shapes of these scattered-ion curves are not easily predictable, it is not possible to accurately infer the effect of the scattered ions on the valley between the 19- and 20-amu peaks.

The value of 46 counts of mass 20-amu ions synthesized in figure 21-4 is most likely as large as could be obtained with any set of assumptions. If it were assumed that the ion-molecule scattering
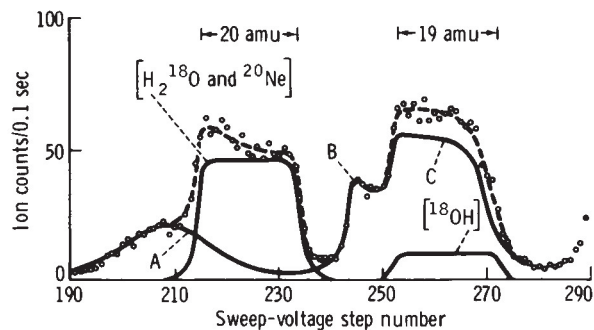

FIGURE 21-4.—Synthesis of the data of figure 21-3. The amplitude of the 20-amu peak, attributable to $H_2^{18}O$ and ^{20}Ne, is found from a least-squares error fit of this peak, a 3-count background, and the Gaussian scatter perturbation labeled A. Scatter is also the origin of hump B, whereas the form denoted C results from a combination of the scatter of water ions and H_3O^+ ions formed by ion-molecule collisions.

background increases gradually from 3 to 5 counts between sweep-voltage steps 190 and 240, then the use of the least-squares curve-fitting process for a Gaussian contribution resulting from scatter would lead to a 20-amu peak of 44 counts. However, the supposition of a Gaussian characteristic for the obstacle-scatter process leads to the largest plausible values of ^{20}Ne. If a non-Gaussian scatter pattern were assumed, then the total peak amplitude resulting from 20-amu ions could be as small as 39 counts. Thus, the probable range of mass 20-amu ions is between 39 and 46 counts. Subtraction of the 35 ± 1 counts known to result from $H_2^{18}O$ leads to an uncertainty in the amount of ^{20}Ne in the range of 3 to 12 counts. Absolute calibration of the Apollo 16 instrument in the MBF at the NASA Langley Research Center (Yeager et al.[3]) showed that 1 count in the data would correspond to 1100 atoms of neon with ram velocity equal to the CSM orbit speed. Thus, at the orbit altitude of approximately 100 km, the concentration of ^{20}Ne is estimated to be approximately $(8.3 \pm 5) \times 10^3$ atoms/cm^3. Because this

[3]Ibid.

concentration is approximately 4 scale heights above the lunar surface at night, the surface concentration must be e^4 times that at orbit altitude, or $(4.5 \pm 3) \times 10^5$ atoms/cm^3. This value is roughly a factor of 3 less than the nighttime estimate of 1.5×10^6 atoms/cm^3 made by Johnson (ref. 21-7) for neon of solar wind origin.

Attempts to determine the amount of lunar ^{22}Ne have been inconclusive because of the large amount of doubly ionized carbon dioxide (CO_2) produced in the ion source. Presumably, most of the CO_2 was of spacecraft origin and reached the instrument after vaporization of particles that had been ejected earlier from the CSM. Peaks at masses 44 and 22 have a nearly constant ratio throughout the flights of both the Apollo 15 and 16 spacecraft, although the levels vary from orbit to orbit and from day to night in each orbit. Preliminary analysis indicates that all of the 22-amu peak is attributable to CO_2^{++}, but the current error estimate is equivalent to several counts. Subsequent data processing should reduce this error and allow a more definitive search for the existence of ^{22}Ne to be made.

The temperature-controlled inlet plenum of the Apollo 16 instrument helped to confirm the conjecture that much of the contamination present in the spectra arises from vaporization of coorbiting particulate matter. The plenum temperature varied less than 2° K throughout an orbit, whereas levels of various contaminants varied as much as a factor of 5 from day to night, with all having daytime maximums. If the walls of the plenum had been an important source, their contribution would have shown significantly less diurnal variation. This observation vindicates the plenum as the major contamination source and supports the coorbiting-particulate-matter theory. Because of a boom malfunction and the subsequent jettisoning of the mass spectrometer just before the Apollo 16 transearth injection burn, it was not possible to confirm the Apollo 15 observation of significantly less contamination in transearth coast than in lunar orbit.

DISCUSSION

The current estimate of the nighttime surface concentration of ^{20}Ne at $(4.5 \pm 3) \times 10^5$ atoms/cm^3 and Johnson's theoretical value of 1.5×10^6 atoms/cm^3 (ref. 21-7) differ by approximately a factor of 3. This is reasonable agreement, considering the uncertainties in the values of solar wind abundance of neon and the photoionization rate assumed by Johnson. A ramification of the near agreement of the experimental and theoretical results is the verification of the assumption made by Johnson that most of the solar wind neon ions that impinge on the Moon (with approximately 1-keV energy) are neutralized and subsequently emitted into the lunar atmosphere. This assumption implies that the surface soil is saturated with neon.

It is important to recognize the implication of the possibility that a real discrepancy exists between the present analysis and the theoretical value of the amount of lunar neon. If the actual amount were much less than the theoretical value, then the surface currently would be absorbing most of the solar wind ions. To maintain the low level of neon in returned fines at less than 1 ppm (ref. 21-8), it would be necessary to continually overturn the soil to a depth of approximately 1 km, if the solar wind flux has remained relatively constant over geologic time. The lack of evidence of recent large-scale overturning of the soil leads to the conclusion that the current neon content in surface materials represents the saturation level, and that any difference between actual and theoretical levels of neon cannot be credited to absorption of solar wind ions.

The current estimate of $(4.5 \pm 3) \times 10^5$ neon atoms/cm^3 is in fair agreement with the data from the Apollo 14 and 15 cold cathode ionization gages operating on the lunar surface. Johnson et al. (ref. 21-1) report that the total concentration in these gages at night is approximately 2×10^5 atoms/cm^3. To aid in correlating the results of these experiments, a laboratory model of the cold cathode gage is to be calibrated in the NASA Langley Research Center MBF under conditions similar to those used in calibration of the lunar orbital mass spectrometers.

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ACKNOWLEDGMENTS