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19. Lunar Orbital Mass Spectrometer Experiment

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The scientific objective of the orbital mass spectrometer experiment is to measure the composition and distribution of the ambient lunar atmosphere. Data from the experiment are applicable to several areas of lunar studies. One such field is the understanding of the origin of the lunar atmosphere. Light gases, such as hydrogen, helium, and neon, probably originate from neutralization of solar-wind ions at the surface of the Moon, while Ar^{40} is most likely due to radioactive decay of K^{40}, and Ar^{36} and Ar^{38} may be expected as spallation products of cosmic ray interactions with surface materials. Molecular gases, such as carbon dioxide, carbon monoxide, hydrogen sulfide, ammonia, sulphur dioxide, and water vapor, may be produced by lunar volcanism.

Another field of application of spectrometer data is related to transport processes in planetary exospheres. The exosphere of the Earth (like that of almost any other planet) is bounded by a dense atmosphere in which hydrodynamic wind systems complicate the problem of specifying appropriate boundary conditions for exospheric transport. This contrasts sharply with the situation in the lunar atmosphere, which is entirely a classical exosphere, with its base the surface of the Moon. The lunar exosphere should be amenable to accurate, analytical study, and experimental determination of the global distributions of lunar gases can provide a reasonable check on theory, giving confidence to the application of theoretical techniques to transport problems in the terrestrial exosphere.[1]

Some of the gases thought to be dominant in the lunar atmosphere are hydrogen, helium, neon, and argon, with the abundance of neon exceeding the others by about an order of magnitude (ref. 19-1).

Hodges and Johnson (ref. 19-2) have recently shown that light gases with negligible production and loss rates tend to be distributed at the lunar surface as the inverse 5/2 power of temperature, while heavier gases are influenced by the rotation of the Moon. Neon falls into the former category, and its concentration on the antisolar side should be about 32 times that on the sunlit side. Its scale height on the dark side is about one-fourth that on the sunlit side, and, thus, at a satellite altitude of 100 km, the diurnal fluctuation of neon concentration should be less than a factor of 2. Argon, being a heavier gas, is expected to be noticeably influenced by the rotation of the Moon. It has a slightly less diurnal variation than neon and a longitudinal shift of its maximum toward sunrise, resulting in a concentration at sunrise that is approximately twice that at sunset.

Water vapor and other condensable gases probably exist in the lunar atmosphere, but not on the dark side, or near the poles, where the surface temperature is below 100 K and adsorption removes every particle that comes in contact with the surface. Gases adsorbed in continuously shadowed regions near the poles are unlikely to reenter the atmosphere, but at lower latitudes the rotation of the Moon transports adsorbed gases into sunlight where they are released into the atmosphere. Since surface heating occurs rapidly, this release probably occurs entirely within a few degrees longitude from the sunrise terminator, creating a pocket of gas.

The firing of the ascent rocket of the lunar module and the impact of the jettisoned lunar module ascent stage with the surface are good examples of known point sources of gas on the lunar surface. If the rate of spreading of these gas clouds around the Moon could be detected by the mass spectrometer in orbit, the diffusion rates for the various gases could be

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[1] Hodges, R.R.: Applicability of a Diffusion Model to Lateral Transport in the Terrestrial and Lunar Exosphere. To be published in Planetary and Space Science.

calculated. Also, the escape rates of gases of various molecular weights could be determined. Because the gases from the rocket will be adsorbed on the lunar surface materials, the measurement of outgassing rates of these adsorbed gases should be useful. From this information, the amount of contamination of the lunar atmosphere due to the firing of rocket motors, both past and future, near the surface could be estimated.

INSTRUMENT

A sector-field, dual-collector, single-focusing mass spectrometer, with its electronics packaged in a controlled thermal environment, is mounted on a 7.3-m bistem boom that is extended from the service module of the Apollo spacecraft. Control of the experiment functions, as well as the boom extension and retraction, is provided by a set of five switches in the command module (CM) operated by a crew member according to the mission time line or by request from the Mission Control Center. The dimensions of the instrument are approximately 30 by 32 by 23 cm, and the weight is 11 kg. Figure 19-1 is a photograph of the mass spectrometer. The scoop mounted on top of the package is a gas inlet plenum that is oriented along the spacecraft velocity vector (the ram direction) when the command-service module (CSM) is flown backwards in its −X direction.

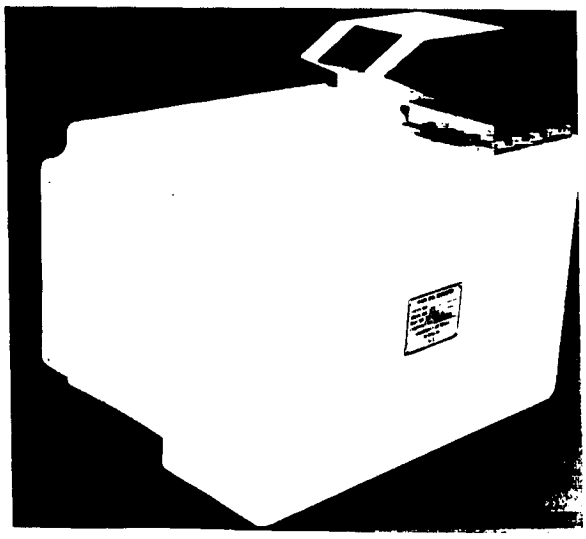


FIGURE 19-1.–Photograph of the lunar orbital mass spectrometer. The plenum containing the ion source is at top of photograph.

The plenum is on the outboard side of the instrument with respect to the CSM, such that the distance to a plane passing through the entrance aperture from any point of the CSM is 5.5 m minimum. In order that a gas molecule emanating from the CSM be detected, it must either undergo a collision within the field of view of the plenum aperture and be deflected into the aperture, or orbit the Moon so as to intersect the path of the plenum aperture. This system was shown to be a very effective discrimination mechanism against direct CSM outgassing by comparative tests in lunar orbit and in transearth coast (TEC), where there were no returning, orbiting particles.

The plenum contains the mass spectrometer ion source (a Nier type) employing redundant tungsten (with 1 percent rhenium) filaments mounted on either side of the ionization chamber. An emission-control circuit activated by the ion source switch (ON position) in the command module powers the filaments. Two small heaters, consisting of ceramic blocks with imbedded resistors, are mounted on the sides of the ionization chamber. In order to outgas the ion source during flight, these heaters are activated by the ion-source switch (STANDBY position). The ion-source temperature reaches 573 K in 15 min. Several outgassing periods during the flight maintained the ion source in a reasonably outgassed state.

When the CSM is oriented to orbit the Moon with the −X-axis forward (flying backward), the instrument plenum angle of attack is near zero and the native gases of the lunar atmosphere are scooped into the plenum. To determine the background spectra from the CSM and the instrument outgassing, the +X spacecraft axis is pointed forward with the plenum aperture in the wake, preventing native gases from entering the plenum.

The mass analyzer is a single-focusing permanent magnet with second-order angle focusing achieved by circular-exit field boundaries, giving a mass resolution of better than 1 percent valley at mass 40 amu. Two collector systems permit simultaneous scanning of two mass ranges, 12 to 28 amu and 28 to 66 amu. Figure 19-2 is a schematic drawing of the analyzer.

Voltage scan is employed utilizing a stepping high-voltage power supply. The ion-accelerating voltage (sweep voltage) is varied in a stepwise manner (590 steps are required to scan the spectra), with a dwell time on each step of 0.1 sec. An enable pulse from the data handling system steps the ion-accelerating voltage. The voltage step number, which de-

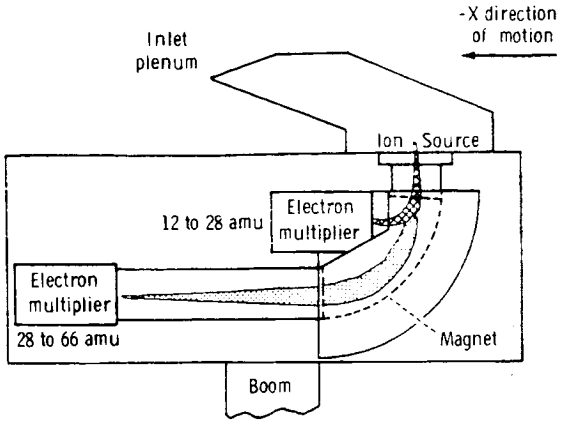


FIGURE 19-2.–Schematic drawing of the magnetic analyzer, showing two ion-beam trajectories.

termines the mass number of the ion being detected, is found by counting from step one, which is indicated by a sweep start flag (Data C). The ion accelerating voltage sweep is generated by varying this voltage in a series of 590 steps from 620 to 1560 V. Between each sweep 30 additional steps at zero V are used to determine background counting rate, and to apply an internal calibration frequency. The sweep start flag (Data C) indicates data or background, and serves as a marker for the start of each sweep. The minimum number of steps between adjacent mass peaks below mass 54 is 12.

The detector systems, employing electron multipliers, preamplifiers, and discriminators, count the number of ions that pass through each collector slit on each of the sweep voltage steps. The ion-count number is stored in a 21-bit accumulator (one for each channel) until sampled by the scientific data system, a 64-kilobit/sec telemetry link to Earth. Just prior to sampling, each data word is compressed pseudologarithmically into a 10-bit word consisting of a 6-bit mantissa and a 4-bit multiplier. This system maintains 7-bit accuracy throughout the 21-bit range of data counts.

Two switches in the CM control the data-counting system. Gain of the electron multipliers is adjustable by controlling the high voltage applied to the multiplier by the MULT switch. The normal operation mode is LOW, but the HIGH position may be used if the multiplier gain should decrease during flight. Similarly, in the discriminator circuit of the pulse-counting system, a sensitivity-level change is selectable by the DISC switch. Normal mode is discriminator HIGH. During the flight the discriminator LOW setting was used to reduce an occasionally high background counting rate due to scattered sunlight in the analyzer. With sufficient multiplier gain, the counting rate ratio at multiplier LOW and discriminator LOW to multiplier HIGH and discriminator HIGH should be greater than 0.95. This condition was met during the flight of this instrument, indicating the ion-counting efficiency was very high.

A housekeeping circuit monitors 15 functions within the instrument that are sampled serially, one per second, by the data system. Parameters, such as certain internal voltages, electron emission in the ion source, filament currents (to determine which filament was operating), multiplier voltages, sweep voltages, temperatures, multiplier and discriminator settings, and instrument current, are monitored.

The mass spectrometer analyzer, magnet, ion source, and detectors are mounted to a baseplate which bisects the instrument package. A conetic housing surrounds these components as is seen in the front portion of the picture of figure 19-1. On the opposite side is a passively controlled thermal environment containing the electronics. Attached to the baseplate is a flange that mates to a similar one on the boom. Opposite to the flange is the plenum that serves as the gas-entrance system to the mass spectrometer.

Thermal control of the electronics is accomplished mainly by a passively controlled environment. An active heating element, a 5-W heater, which is operated by a thermal control circuit, is attached to the interior of the electronics housing. It is powered at temperatures below 273 K and is turned off at 279 K. During the Apollo 15 mission, the heater was inoperative as the electronics temperature remained between 278 and 313 K, indicating that the passive thermal system was adequate to protect the electronics from the lunar and interplanetary environments.

CALIBRATION

Initial calibration of the mass spectrometers, performed in a high-vacuum chamber at The University of Texas at Dallas, verified that the proper mass ranges were scanned, and tested the resolution, linearity, mass discrimination, and dynamic range of the analyzer. Neon was introduced into the vacuum chamber with isotopic partial pressures ranging from

10^{-11} to 10^{-7} torr. As is shown in figure 19-3, the instrument response was linear up to 1×10^{-8} torr where the onset of saturation of the data-counting system occurred. The sensitivity of the instrument was verified to be greater than 3×10^{-5} A/torr, enabling the instrument to measure partial pressures down to 10^{-13} torr. The uncertainties in the introduction of gases into the chamber, in the pressure measurement, and in the wall effects precluded the determination of the absolute sensitivity in The University of Texas at Dallas chamber. The absolute calibration was performed in the NASA Langley Research Center Molecular Beam Facility (MBF) as reported by Yeager et al.[2]

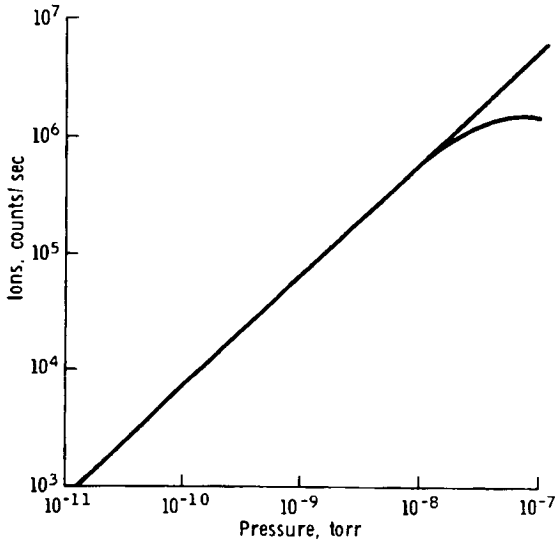


FIGURE 19-3.–Dynamic range of the mass spectrometer for neon, including neon-21 and neon-22 peaks to extend the pressure range.

The molecular beam system used for this experiment is shown schematically in figure 19-4. A high-pressure gas source was required to maintain inlet pressures from 0.1 to 10^4 torr, at a constant known temperature between 295 and 301 K. The high source pressure was then reduced by passing the gas through a porous silicate-glass plug into a molecular furnace. The conductance of the plug C_p was experimentally determined (in situ) for all test gases. Gas molecules, upon entering the molecular furnace, equilibrated to the known wall temperature, and effused through a precision aperture into a beam with an angular distribution determined by the Knudsen

[2] Yeager, P.; Smith, A.; Jackson, J.J.; and Hoffman, J.H.: Absolute Calibration of Apollo Lunar Orbital Mass Spectrometer. To be published in Journal of Applied Physics.

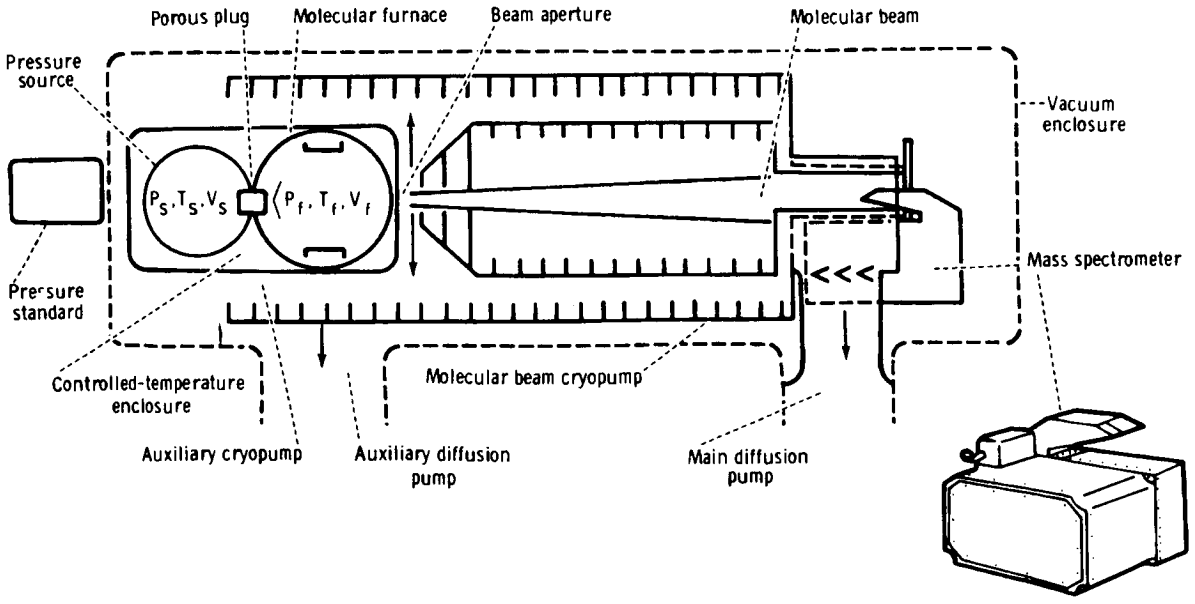


FIGURE 19-4.–Sketch of the Molecular Beam Facility at the NASA Langley Research Center. Pressure, temperature, and volume (P, T, and V) are indicated by subscript as source S and furnace f.

cosine law. The beam passed through a set of cryo baffles at 4.2 K and through a copper tube, also at 4.2 K, into the mass spectrometer plenum, the axis of which was alined with the beam axis.

The mass spectrometer was mounted in the MBF with the electronic package in the guard vacuum of the system and the plenum located as described previously. An externally controlled mechanical linkage allowed the plenum-beam angle to be varied from 0° to 40° with reference to a horizontal axis perpendicular to the beam axis (the spacecraft yaw direction). Pitch angles of −5°, 0°, and +5° (with reference to a vertical axis perpendicular to the beam axis) could be set manually with the system open. Separate tests were conducted with a combination of the three pitch angles and various yaw angles from 0° to 40°. The mass spectrometer inlet was completely enclosed by a 4.2 K extension copper tube so that the back scattering of molecules into the inlet is essentially eliminated. The 4.2 K extension tube was enclosed by a 77 K wall of the guard system.

A large amount of data was generated from these tests using three flight instruments and one qualification model. Figure 19-5 shows a typical set of curves of the output counting rate for neon and argon as a function of MBF beam flux; 10^{10} molecules/cm^2-sec is equivalent to 6.5×10^{-12} torr of argon in the plenum. It can be seen that pressures below 10^{-13} torr in the plenum are readily measurable. The data show a linear response well within the molecular beam accuracy (6 percent).

Figure 19-6 shows the variations in output for the flight units with change in yaw angle. Up to about 20° the output falls off according to the cosine law, as would be expected. However, between 20° and 40° the fall-off is close to a cos^2 function. This seems to be due to incoming molecules not reaching equilibrium with the walls before they are measured or escape from the plenum. Up to 20° yaw, the input beam hits the rear wall of the plenum only. Beyond 20°, it begins to strike the side walls from which gas molecules may more readily escape without being measured. The qualification model was also tested at +5° and −5° pitch angles. The output at negative pitch angles is higher than for positive pitch angles. This is due to the shape of the inlet and the resulting in and out gas flux. The inlet opening is not perpendicular to the direction of the beam, but becomes more nearly so at negative pitch angles. This results in the effective beam opening being smaller than the actual exit size for an incoming beam, but

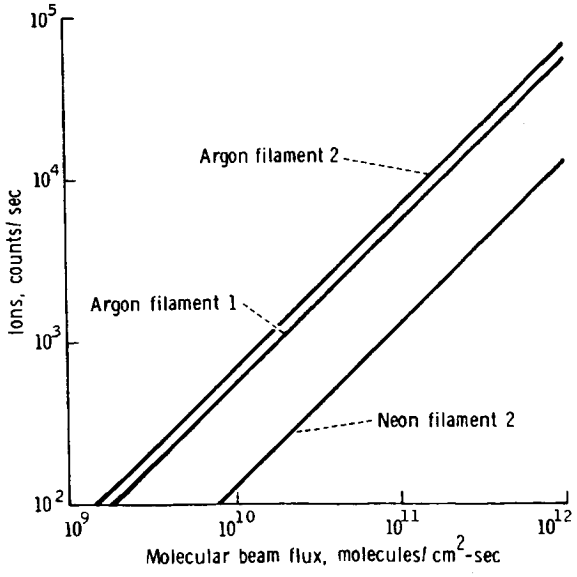
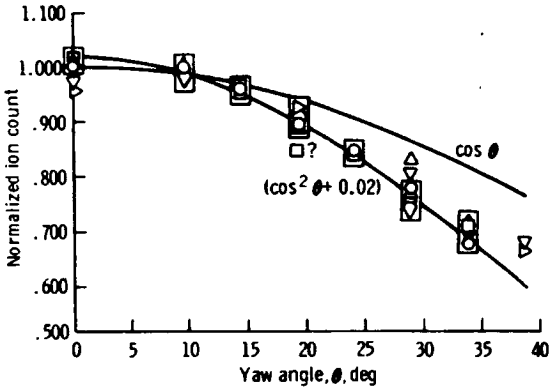


FIGURE 19-5.–Calibration of mass spectrometer output as a function of molecular beam flux for neon and argon. Combining these results with figure 19-3 gives a dynamic range of nearly 6 decades.



Symbol	Gas	Unit	Pressure, N/m^2	Pitch angle, deg
○	Argon	Flight 1	2.06 x 10^5	0
□	Neon	Flight 1	2.06	0
◇	Argon	Flight 2	2.06	-5
△	Neon	Flight 2	2.06	-5
▽	Argon	Qualification model	2.06	+5
▷	Neon	Qualification model	6.88 x 10^4	+5

FIGURE 19-6.–Angular response of the mass spectrometer to off-axis beams. Flight Unit 3 data are within the bounded region shown for Flight Units 1 and 2.

remaining the geometrical opening for the outgoing flux. The measured pitch angle response follows a cosine law.

During flight, the instrument is mounted on a long boom which is susceptible to thermal twisting, equivalent to a spacecraft yaw maneuver, and bending, equivalent to a pitch motion. Preliminary results from the flight indicate the boom did twist as a function of the Sun angle by an amount very close to that predicted by models of boom twist, 35° to 40°. The bending was very slight.

RESULTS

The mass spectrometer experiment produced about 40 hours of data in lunar orbit and 50 additional hours during TEC. Instrument performance was quite satisfactory. Preliminary quick-look-type data showed large numbers of peaks in the mass spectra of relatively large amplitude. Figure 19-7 shows typical spectra from lunar orbit. The peak amplitudes (counts per second) are plotted as a function of sweep-voltage step number. The upper spectrum shows peaks from 66 amu to 27 amu; the lower shows peaks from 28 amu to 12 amu. The mass 18 peak (water vapor) saturated the counting system.

In figure 19-8 the counting rates for three gases are plotted as a function of ground elapsed time (GET), showing diurnal variations in lunar orbit and the same constituents during the passive-thermal-control attitude of TEC. During TEC the amplitude of all peaks has decreased by a factor in the range of 5 to 10. Also during TEC, a boom-retraction test, reducing the boom length in four steps to 1.25 m, showed no increase in any gas constituent. This implies that the mass spectrometer plenum is very effective in preventing molecules originating at the CSM from entering the ion source. Such outgassing molecules form essentially a collisionless gas within 1.25 m from the CSM surface.

The major gases observed in lunar orbit do not appear to have a significant velocity with respect to the spacecraft as the observed densities are not a

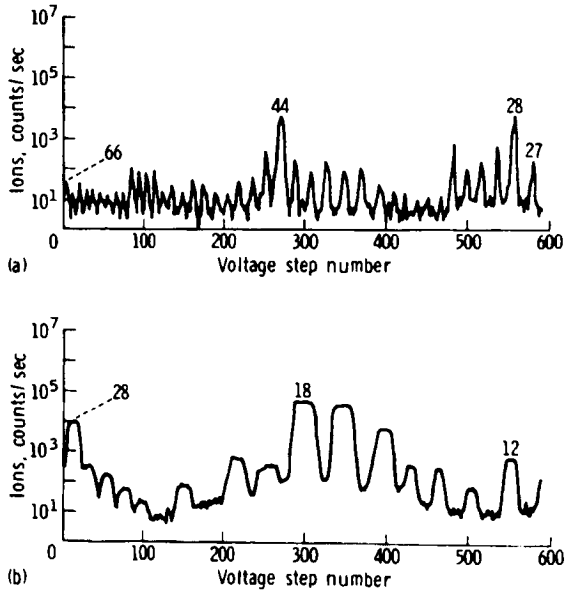


FIGURE 19-7.–Mass spectra for lunar orbit. (a) High mass range from 66 to 27 amu. (b) Low mass range from 28 to 12 amu.

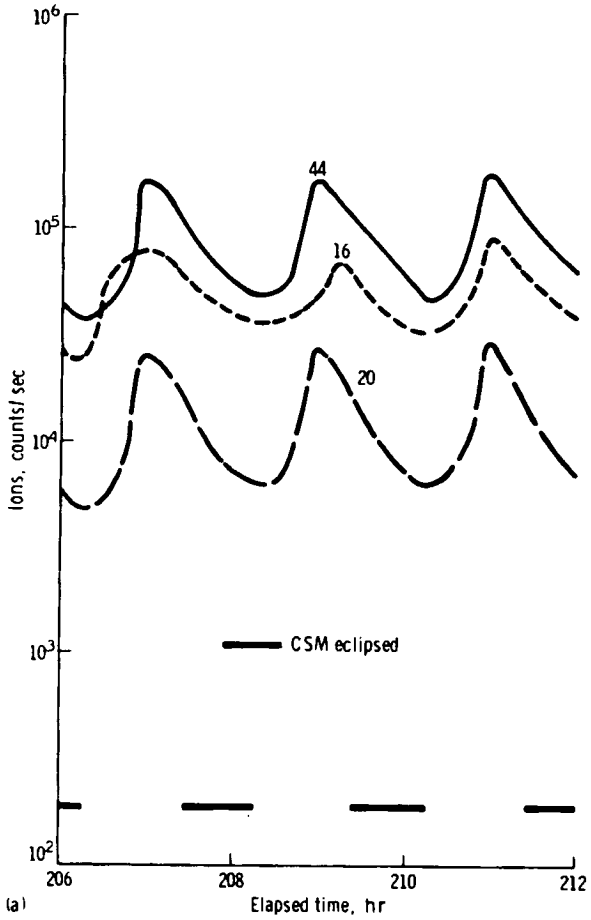
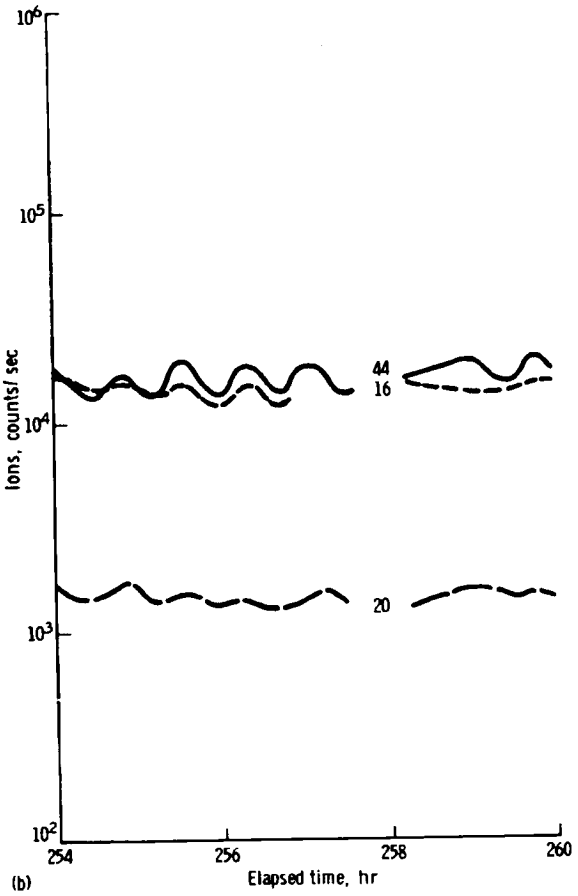


FIGURE 19-8.--Mass spectrometer data for three gas species. (a) Data recorded during lunar orbit. (b) Data recorded in passive-thermal-control attitude of TEC.



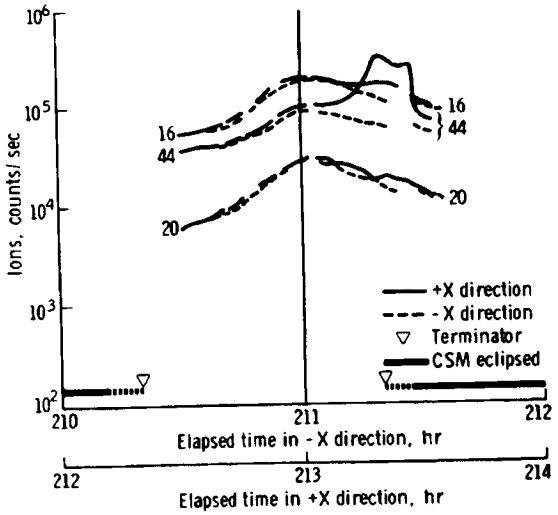


FIGURE 19-9.–Data from lunar orbit for –X (ram) and +X (wake) orientations for selected mass peaks.

function of the angle of attack of the instrument plenum. These are probably of spacecraft origin, orbiting the moon with the CSM.

Figure 19-9 is a plot of several gas species counting rates for two successive revolutions about the Moon, the first in –X forward CSM orientation, the second in +X. Except for the region near the terminator where the mass 44 peak (probably carbon dioxide) exhibits a large increase, the amplitudes (gas concentrations) of all peaks are essentially independent of plenum orientation.

CONCLUSION

The lunar orbital mass spectrometer experiment, from reduction of a small amount of quick-look data, appears to have operated successfully, observing a large number of gas molecules in the vicinity of the spacecraft in lunar orbit. Many of these molecules are most likely of spacecraft origin, orbiting the Moon with the CSM. Interesting variations of this gas cloud are observed as a function of orbital parameters, but extensive analysis of the complete set of data soon to become available from tapes recorded during the mission will be required to understand the significance of these results.

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