LUNAR BASE ACTIVITIES AND THE LUNAR ENVIRONMENT

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The Moon is an attractive site for astronomical observatories and other facilities because of the absence of a substantial lunar atmosphere and the stability of the lunar surface. The present lunar atmosphere is sufficiently transparent that there is no significant image distortion due to absorption or refraction. This thin atmosphere results from a combination of small sources and prompt losses. The major source that has been identified is the solar wind, whose total mass input into the lunar atmosphere is approximately 50 gm/sec. The major components of the solar wind are light elements (H and He) that promptly escape from the lunar surface by exospheric evaporation (Jeans' escape). The principal atmospheric loss mechanism for heavier gases is photoionization within a period of weeks to months, followed by immediate loss to the solar wind. Lunar base activities will modify the lunar atmosphere if gas is released at a larger rate than that now occurring naturally. Possible gas sources are rocket exhaust, processing of lunar materials, venting of pressurized volumes, and astronaut life support systems. For even modest lunar base activity, such sources will substantially exceed natural sources, although effects are expected to be localized and transient. The Apollo database serves as a useful reference for both measurements of the natural lunar environment and its modification by lunar base activities.

INTRODUCTION

The absence of a substantial lunar atmosphere makes the Moon an attractive site for astronomical observatories and for materials processing facilities that require a high vacuum. The present lunar atmosphere is sufficiently transparent that there is no significant image distortion due to absorption or refraction. Furthermore, the absence of a significant lunar ionosphere allows the use of the Moon for radio astronomy at frequencies much lower than those observed with terrestrial observatories. Other benefits to lunar base activities are the surface stability that facilitates the construction of large arrays, the lack of erosion or wind loading, and the availability of ample shielding from space radiation. These unique conditions at the lunar surface will enable the operation of science facilities not feasible elsewhere (*Mendell*, 1985).

To evaluate quantitatively the operational capabilities of lunar science facilities, it is necessary both to specify the natural lunar environment and to assess the alterations to it that might result from lunar base activities. Fortunately, many of the physical environmental conditions at the lunar surface were measured during the Apollo program. In particular, several sensors measured the neutral and ionized gases at the lunar surface. Although these measurements were limited both spatially and temporally, they have been used to identify the sources of the natural lunar atmosphere and ionosphere, as well as the loss processes that are effective in the lunar environment.

Lunar base activities can modify the lunar atmosphere by gas release at a larger rate than is now occurring naturally. Possible gas sources, such as rocket exhaust and astronaut life support systems, can be estimated from the experiences of the Apollo program. The Apollo database serves as a useful reference for both measurements of the natural lunar environment and its modifications by manned activities. Although no specific experiments were performed and measurements were not comprehensive, data do exist for several artificial releases such as the lunar module liftoff, S-IVB impacts, and cabin vents. During the Apollo missions rocket exhaust was a substantial, although transient, addition to the lunar atmosphere.

This paper reviews the characteristics of the natural lunar atmospheres and ionospheres, including known sources and loss processes. The gas sources expected to be associated with lunar base activities are identified, and the expected release rates are calculated. The Apollo data relevant to atmospheric alteration are briefly discussed. Finally, several recommendations are made for investigations that need to be made in support of a lunar base program.

CHARACTERISTICS OF THE LUNAR ATMOSPHERE

Prior to the Apollo program little was known about the lunar atmosphere except that it is very transparent to both light and radiowaves, implying that surface densities of both neutral and ionized gases are very small (*Johnson*, 1971).

Several kinds of atmospheric and ionospheric monitors were placed on the lunar surface as part of the Apollo Lunar Surface Experiments Package (ALSEP) during the Apollo program. The Cold Cathode Gauge Experiment (CCGE) and the Lunar Atmospheric Composition Experiment (LACE) measured the density and flux of neutral gases, and the Suprathermal Ion Detector Experiment (SIDE) measured the flux of atmospheric ions. Surface photoelectrons and the lunar plasma environment

were detected by the Charged Particle Lunar Environment Experiment (CPLEE) and the Solar Wind Spectrometer (SWS). The locations of these instruments are summarized in Table 1.

TABLE 1.   ALSEP atmosphere and ionosphere observations.

Instrument	Missions	Phenomenon
CCGE	12, 14, 15	Total gas pressure
LACE	17	Nightside atmospheric composition
SIDE	12, 14, 15	Atmospheric ions
CPLEE	14	Surface photoelectrons
SWS	12, 15	Solar wind plasma

The CCGE was a total pressure monitor that provided the first estimates of the number density of neutral gases at the lunar surface (*Johnson et al.*, 1972). The observed nighttime concentration was about $2 \times 10^5 \, cm^{-3}$. The daytime value was $10^7 \, cm^{-3}$, but was thought to be an upper limit because the measurements were presumed to be affected by local contamination.

The most sensitive instrument for detection of lunar atmospheric gases was the LACE, which was deployed only on the last Apollo mission. This neutral gas mass spectrometer was able to detect atmospheric gases with excellent resolution and high sensitivity (*Hoffman et al.*, 1973). During the nine months of operation, useful data for most gases were generally obtained only during the lunar night. During the entire night, measurements were made of Ar, Ne, and He. Gases that condense on the lunar darkside, such as CH_4, NH_3, and CO_2, were measured only for a limited time just prior to sunrise (*Hoffman and Hodges*, 1975). Their daytime abundance (see Fig. 1) can be calculated from the solar wind source intensity and the modeling of atmospheric dynamics (*Hodges*, 1976).

The final instrument providing atmospheric information was the SIDE. Each SIDE contained two ion detectors that monitored ions originating from the lunar atmosphere and from gases released during Apollo missions, as well as ions from the Earth's magnetosphere and the solar wind (*Freeman et al.*, 1971, 1973; *Lindemann et al.*, 1973). An important feature of the SIDE network was its ability to monitor the local atmosphere density by a variety of methods (*Freeman and Benson*, 1977). Also, since the detectors relied on an exterior electric field to accelerate the ions, they were less sensitive to contamination due to internal instrument degassing. The SIDE measurements on the dayside were consistent with the gas concentrations measured by the CCGE and inferred from the LACE data, assuming that molecular species are present on the dayside in addition to the inert gases (*Vondrak et al.*, 1974).

Sodium and K have recently been detected in the lunar atmosphere by ground-level spectroscopic observations (*Potter and Morgan*, 1988). The surface densities of these elements are quite small (less than $10^2 \, cm^{-3}$), and are thought to originate from the vaporization of surface minerals by meteoric impact or solar wind sputtering.

The concentrations of the lunar atmospheric species are indicated in Table 2. The predominant dayside species is CO_2, and Ne is the predominant nightside gas. The total atmospheric mass globally integrated for each species is shown in Table 3. The quantities of gases temporarily adsorbed on the lunar surface exceed these amounts by factors of about 1000. The quantities shown in Tables 2 and 3 are based on measurements and inferences from the Apollo and other data. However, it should be kept in mind that the limited observations result in significant uncertainties, especially for the molecular gases. In particular, the quantities shown for each of the carbon compounds are overestimates because the calculations by *Hodges* (1976) assumed that all the solar wind carbon was the source of each particular compound.

The quantities of gases in the lunar atmosphere are quite small. For comparison, the terrestrial atmosphere concentrations are approximately $10^{19} \, cm^{-3}$ at the Earth's surface and are as little as 10^5 to $10^7 \, cm^{-3}$ at altitudes between 500 km and 1500 km.

The thin lunar atmosphere results from a balance between small sources and rapid losses. The primary source of the lunar atmosphere is the solar wind. Because the Moon lacks any
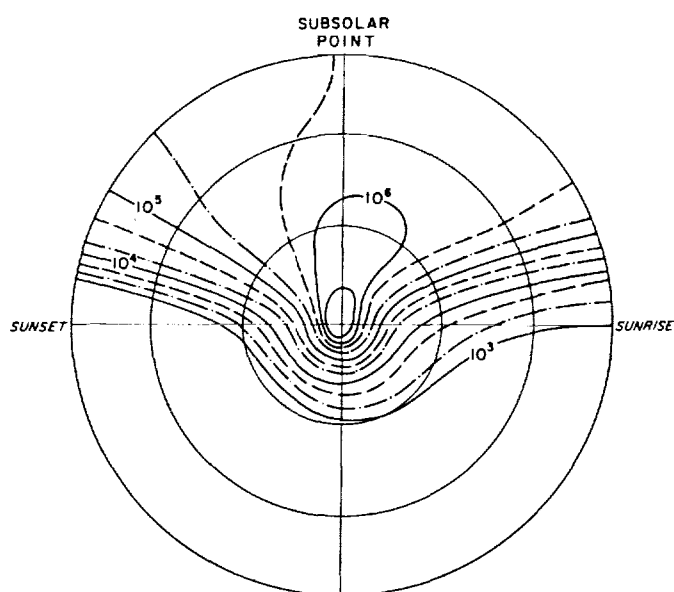

Fig. 1.   Stereographic projection of the distribution of carbon dioxide (CO_2) on the northern hemisphere of the Moon (*Hodges*, 1976).

TABLE 2.   Lunar atmosphere concentrations.

Species	Daytime (cm^{-3})	Night (cm^{-3})
H_2	4×10^3	1.2×10^4
^4He	2×10^3	4×10^4
^{20}Ne	4×10^3	1×10^5
^{36}Ar	1×10^2	3×10^3
^{40}Ar	1.6×10^3	4×10^4
CO	3×10^5	$<10^3$
CO_2	6×10^5	$<10^3$
CH_4	7×10^4	$<10^3$
Na	6.7×10^1	
K	1.5×10^1	

TABLE 3.   Total atmospheric mass.

Species	Mass (kg)
CO_2	5200
CO	2000
CH_4	640
Ne, Ar	<500

substantial intrinsic magnetic field or thick atmosphere, the solar wind flows directly onto the lunar surface. The flux and composition of the solar wind have been measured by spacecraft instruments (e.g., *Bochsler*, 1989; *Bochsler et al.*, 1986). The typical total flux of solar wind species on the sunward hemisphere of the Moon is listed in Table 4. The solar wind ions impact the lunar surface, are thermalized and perhaps chemically altered there, and are then released as neutral atoms or molecules that travel along collision-free ballistic trajectories between impacts with the surface. Although the total solar wind mass input to the lunar surface is about 50 gm/sec, the major components are the light elements H and He. The thermalized H and He have velocities greater than the lunar escape velocity and are rapidly lost from the lunar environment. The total mass input by the heavier elements in the solar wind that reside longer in the lunar atmosphere is less than 1 gm/sec.

Other possible sources of the lunar atmosphere are material released or weathered from the lunar surface, or gases released from the lunar interior. As discussed above, surface weathering results in small quantities of Na and K. The only endogenous gases that have been conclusively identified are Ar and Rn, decay products of radioactive materials in the lunar interior. About 10% of the He in the lunar atmosphere is thought to be of radiogenic origin (*Hodges*, 1977). The most important is ^{40}Ar, originating from K. The total source rate of ^{40}Ar is about 0.06 gm/sec, and is about an order of magnitude larger than the solar wind input of ^{36}Ar (*Hodges and Hoffman*, 1974). Although larger sources due to the localized release of gases have been suggested in association with lunar transient phenomena (*Middlehurst*, 1967), none has been conclusively identified or measured. The LACE found evidence for a time variation in the abundance of ^{40}Ar, possibly related to lunar teleseismic events (*Hodges and Hoffman*, 1974), but found no unambiguous transient increase in the abundance of other gases. An extensive analysis of SIDE data likewise failed to uncover any transient increases in the lunar atmosphere (*Freeman and Benson*, 1977), and these data were used to set upper limits to transient outgassing from specific sites on the lunar surface (*Vondrak*, 1977).

The neutral atmosphere of the Moon is lost into space by two mechanisms: loss to the solar wind and thermal escape. Mass is lost to the solar wind because atmospheric ions are driven into space by the interplanetary electric field that results from the flow of the interplanetary magnetic field past the Moon (*Manka and Michel*, 1971). Such ion pickup has been observed at Halley's Comet and in artificial chemical releases in space. The time constant for loss by this process is determined by the photoionization lifetime (typically 10^6 to 10^7 sec). Thermal escape results from the fact that the gases in the lunar atmosphere travel along collisionless ballistic trajectories in the lunar gravitational field until they impact the surface or escape into space. Gases that do

TABLE 4. Solar wind flux to lunar surface.

Element	Flux (gm/sec)
Hydrogen (^{1}H)	40
Helium (^{4}He)	8
Oxygen (^{16}O)	0.2
Carbon (^{12}C)	0.1
Neon (^{20}Ne)	0.07
Nitrogen (^{14}N)	0.03
Silicon (^{28}Si)	0.05
Argon (^{36}Ar)	0.004

impact the surface are briefly adsorbed by the surface material (*Cadenhead et al.*, 1972). The gases come into thermal equilibrium with the lunar surface before desorbing. When they are emitted from the surface, a fraction has sufficient thermal energy to escape from the lunar gravity field. This loss of the faster-moving exospheric gases is referred to as evaporative loss or Jeans' escape (*Jeans*, 1923). The atmospheric loss rate by this process is dependent upon the mass and temperature of the gases. For the two lightest atmospheric species, H and He, the thermal escape time constant is several thousand seconds. For all other atmospheric gases the thermal escape time constant is very long (e.g., 190 years for Ne and 10^{10} years for Ar), much longer than the time constant for solar-wind-induced mass loss (*Johnson*, 1971).

THE LUNAR IONOSPHERE AND PLASMA ENVIRONMENT

Extensive investigations of the lunar plasma environment made during the Apollo program have shown that, like the Earth, the Moon is surrounded by a region of ionized plasma. However, unlike the terrestrial ionosphere, the lunar ionosphere is directly coupled to the solar wind by the interplanetary electric field. As a result, the lunar atmospheric ion fluxes are both directional and variable and the ions have a nonthermal energy distribution. Collisions within the ionosphere are unimportant, and interactions with the lunar surface control the ionospheric chemistry. In addition to this ionosphere of lunar origin, the region surrounding the Moon is permeated by the interplanetary and magnetospheric plasma.

The lowest part of the lunar ionosphere consists of a thin, dense sheath surrounding the Moon as a result of the electric potential of the lunar surface. Measurements by the SIDE (*Fenner et al.*, 1973) and CPLEE (*Reasoner and Burk*, 1972) have demonstrated that the surface potential is positive on the dayside, at a value of about 30 V with respect to the solar wind. There the sheath consists of a photoelectron layer with an electron density at the surface of about 10^4/cm^3 and an altitude extent of several hundred meters (*Reasoner and Burke*, 1972). Near the sunrise and sunset terminators and on the nightside the lunar surface potential becomes negative (*Manka and Michel*, 1971).

The most extensive part of the lunar ionosphere consists of ions produced from the lunar atmosphere. The neutral atmospheric gases are ionized by the solar ultraviolet photons and by charge transfer with the solar wind in a time of typically 10^6 to 10^7 sec (*Siscoe and Mukherjee*, 1972). These ions are then accelerated by the interplanetary electric field (typically 1-3 mV/m) and are driven either into space or into the lunar surface. As shown in Fig. 2, the initial motion of an ion is in the direction of the solar wind electric field. Ions formed on the dayside in the lower hemisphere (with respect to the electric field) are generally driven into the lunar surface. Ions formed in the upper hemisphere escape into the solar wind because the magnetic force curves the ions in the direction of the solar wind flow with a resulting cycloidal orbit that carries them away from the Moon. Thus, on the lunar dayside the interplanetary electric field drives approximately 50% of the atmospheric ions into space (*Manka and Michel*, 1971; *Vondrak et al.*, 1974).

The flux and energy distribution of the atmospheric ions can be easily calculated for the region where ions are driven directly into the lunar surface by the interplanetary electric field. As shown in Fig. 3, we assume that the neutral atmosphere is distributed
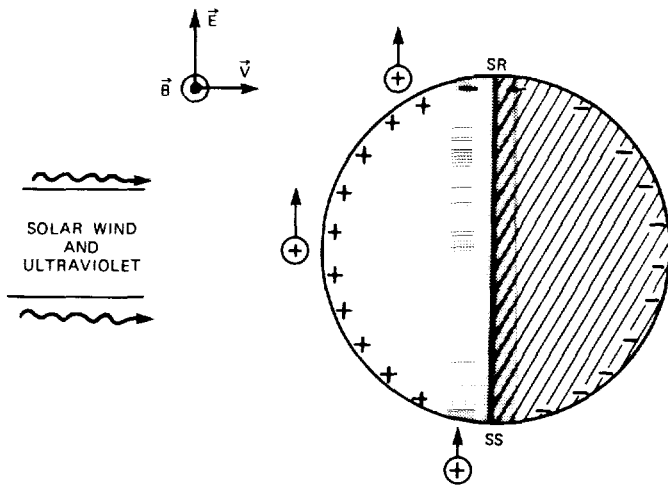
Fig. 2. Schematic representation of the sources of the electric fields near the northern hemisphere of the Moon. The interplanetary electric field is due to the motion of the solar wind magnetic field, and the lunar surface electric field arises from charges on the lunar surface. The shaded area near the terminator is where the potential is negative and the lunar atmosphere is exposed to ionizing solar radiation (*Vondrak et al.*, 1974).

$$E \simeq 1\text{-}3 \ \text{V/km}$$

$$H \simeq 20\text{-}100 \ \text{km}$$

$$P \simeq 10^{-6} - 10^{-7}/\text{sec}$$

PRODUCTION RATE $= P n(z)$

ENERGY DISTRIBUTION: $\quad F(\mathcal{E}) = \dfrac{P n_o}{q E} e^{-z/H} e^{-\mathcal{E}/qEH}$

INTEGRAL FLUX $= P n_o H e^{-z/H}$

DENSITY: $\quad \rho = P n_o \sqrt{\dfrac{\pi}{2} \dfrac{mH}{qE}} \ e^{-z/H}$
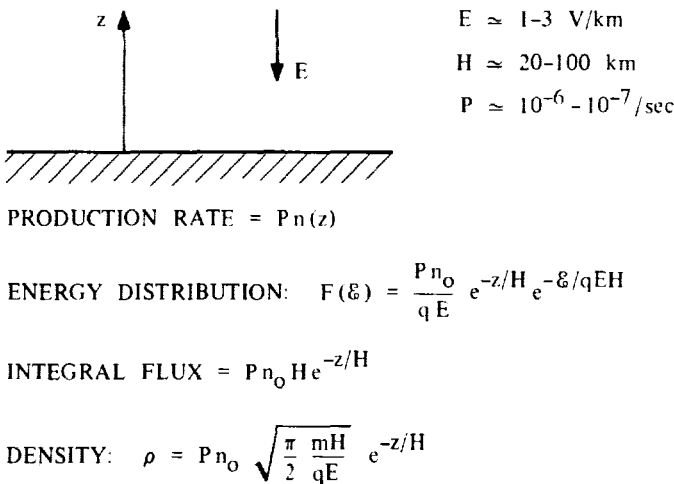
Fig. 3. Flux and density of lunar atmospheric ions at the lunar surface when the interplanetary electric field is pointed downward.

exponentially in altitude with a scale height H. The scale height H for a gas of mean molecular mass m is equal to kT/mg, where T is the temperature, k is Boltzmann's constant, and g is the surface gravitational acceleration. This distribution applies to both collisional atmospheres and thin exospheres (*Johnson*, 1971). If the ions are accelerated by a uniform interplanetary field of magnitude E, then they will have an altitude distribution that is also exponential according to the neutral gas scale height H (*Benson et al.*, 1975). The ions will have a residence time of only a few seconds before impacting the surface. The resulting energy distribution is strongly nonthermal and the differential energy flux for an ion of charge q is an exponential distribution with a folding energy equal to qEH (typically 20-300 eV). The SIDE measure-

ments of the differential energy distribution of the lunar atmospheric ions are consistent with such an exponential altitude distribution. The production rate of these atmospheric ions is proportional to the product of neutral number density and ionization rate. Consequently, the density and flux of the atmospheric ions vary, being directly responsive to changes in the solar wind flux and transient outgassing from the lunar surface. The altitude variation of the density of lunar atmospheric ions is shown in Fig. 4, where we have assumed E = 1 mV/M and H = 50 km. The subsolar photoelectron layer is shown for comparison (*Reasoner and Burke*, 1972). Because of the electric potential of the lunar surface, there is a lack of charge neutrality in the plasma near the lunar surface.

In addition to the ionospheric plasma of lunar origin (the photoelectron layer and lunar atmospheric ions), the Moon is exposed to plasma of extralunar origin (the solar wind, mangeto-spheric plasma, and cosmic rays). Because the Moon lacks shielding by either a strong magnetic field or dense atmosphere, these extralunar plasmas penetrate directly to the surface where they have been regularly observed by the SIDE, CPLEE, and SWS. As shown in Fig. 5, during each orbit the Moon spends about 20 days in the solar wind, 4 days in the magnetosheath (thermalized solar wind plasma), and 4 days within the magnetospheric plasma sheet.

ALTERATION OF THE LUNAR ATMOSPHERE BY LUNAR BASE ACTIVITIES

Because the lunar atmosphere and ionosphere is so tenuous, it is susceptible to alteration by human activity at the lunar surface. Lunar base activities can modify the lunar atmosphere by gas release at a larger rate than is now occurring naturally. Possible gas sources are rocket exhaust, gas release from processing lunar materials, venting of pressurized volumes, and astronaut life support systems. These rates can be estimated from the experience of the Apollo program (see Table 5).

For Apollo, rocket exhaust was a substantial, although transient addition to the lunar atmosphere (see Fig. 6). Each Apollo mission deposited nearly 10^4 kg of rocket exhaust into the lunar
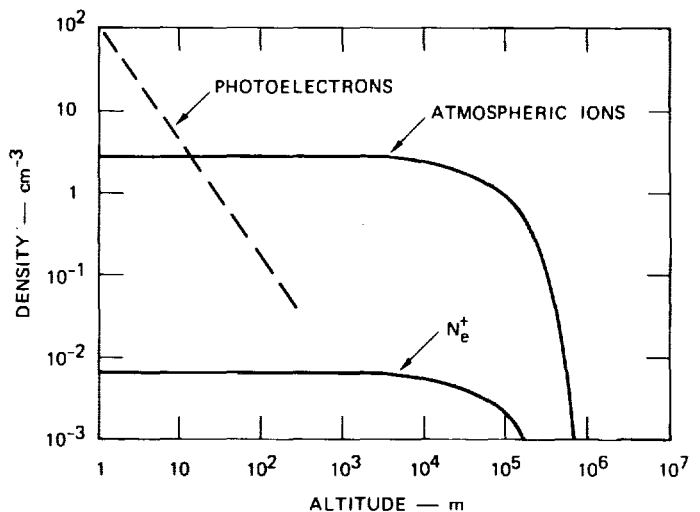

Fig. 4. Altitude variations of photoelectrons and lunar atmospheric ions.
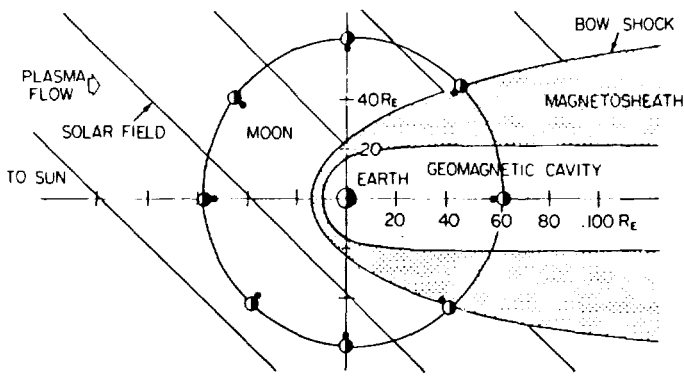
,Fig. 5. Schematic diagram showing the three plasma regions traversed by the Moon. The plane of the figure is essentially the ecliptic plane.

TABLE 5. Artificial sources of atmospheric gases.

Source	Quantity
Lunar module landing/ascent	3000 kg
Apollo CSM return	5000 kg
Lunar module cabin venting	3 kg
Airlock venting (1000 ft³)	27 kg
Astronaut suit	0.3 gm/sec (H_2O)
Structural leakage	0.1 mg/m²-sec
Trapped gases in soil	0.1 g/kg

Fig. 6. Conceptual representation of the effect of Apollo lunar module exhaust gases on the lunar environment. The FAR SIDE cartoon by Gary Larson is reprinted by permission of Chronicle Features, San Francisco, California.

environment. However, since Apollo missions occurred infrequently, no long-lived increase in the lunar atmosphere was produced. A permanent lunar base might result in gas release at a rate equivalent to 10^{-2} kg-sec^{-1} per person, assuming supply traffic equal to one Apollo mission month^{-1} per person. Therefore, even small lunar basees would add gases to the lunar environment at a greater rate than natural sources. Another potential source of gas contamination is mining of the lunar surface. Examination of the lunar samples indicates that about 10^{-4} of the mass of the

lunar soil consists of trapped gases. Perhaps 10% of these gases will be released during upheaval and heating of the soil in normal mining operations. Construction of large structures in space has been proposed by O'Neill (1974) that would require the removal of about 10^9 kg of soil from the lunar surface. Mining this amount would yield only about 10^4 kg of gases, so this does not appear to be a significant source of atmospheric contamination. However, vigorous lunar base activity for mining of rocket propellant or He^3 could result in more substantial release rates.

Gas leakage rates from pressurized structures are difficult to estimate. The Gemini and Apollo space capsules had passive leakage rates of 10 and 30 mg/sec, respectively. These leakage rates were due to continuous diffusion through the cabin walls and outgassing through small leaks, and do not include gas release from thruster firings and cabin ventings. These and Skylab leakage measurements, as well as space station design specifications, indicate a minimum passive leakage rate of about 0.2 mg/m²-sec for current-technology spacecraft. Improved sealing technology and system design during the next 30 years are expected to reduce the rate by not more than a factor of 10 (*Nishioka et al.*, 1973). To exceed the natural source rate of 10 gm/sec, the surface area of the lunar base pressurized areas would have to be more than 50,000 m². The use of partially pressurized airlocks would possibly be a more significant source of gas venting than leakage from the sealed structures.

The consequences of lunar atmospheric modification are a localized increase in atmosphere absorption and light scattering. Because of the reduced gravity on the Moon, the effects of even localized releases spread out to distances of hundreds of kilometers. Dispersal beyond that distance depends on the degree of gas absorption by the lunar regolith. The manner in which neutral gases are transported across the lunar surface has been analyzed by several methods (*Vogel,* 1966; *Milford and Pomilla,* 1967; *Hodges,* 1972; *Hodges et al.,* 1972; *Hall,* 1973; *Burns et al.,* 1991). All these transport calculations assume that no collective plasma effects are important and that the gases move on individual trajectories because the mean free path is greater than the hop distance. The dispersal rate and spatial distribution depend on the source intensity and duration, and the surface retention characteristics. The analyses also indicate that the propagation of gas clouds can be separated into two regions: the direct flux near the source, which describes the initial gas flow, and the diffusive flux whereby gases propagate to greater distances. The direct flux will extend laterally to about two scale heights, typically 100 km, which is the limit of significant gas transport if all gases stick to the lunar surface. If the gases are only adsorbed and subsequently reemitted, they will gradually spread to much larger distances. Because the gases spread rapidly over large areas, gas releases associated with moderate injection rates (approximately 1 kg/sec) are not expected to be a detriment to astronomical observations and high-vacuum materials processing (*Burns et al.,* 1991).

LONG-LIVED ALTERATION OF THE LUNAR ATMOSPHERE

Lunar base activities described in the preceding section are not significant because the solar wind is able to rapidly remove gases added to the thin lunar atmosphere, with a photoionization time constant of weeks to months. However, if the lunar atmosphere were to become more dense, loss to the solar wind would be ineffective and thermal escape from the exosphere would become

the dominant loss mechanism. The lunar atmosphere would then be long-lived since thermal escape lifetimes are at least several hundred years for gases heavier than He (*Johnson*, 1971).

The solar wind loss mechanism is the dominant process only as long as the solar wind has direct access to the majority of the atmosphere. As the atmosphere becomes more dense, newly formed ions of atmospheric origin load down the solar wind and cause it to be diverted around the Moon (see Fig. 7). The effectiveness of the lunar atmosphere loss mechanisms for varying atmospheric total density has been evaluated quantitatively by *Vondrak* (1974, 1976) for an oxygen atmosphere. The exospheric loss rate to the solar wind was calculated by assuming that the total ionization rate was 5×10^{-6} ions per atom sec^{-1} and that half of the exospheric mass was on the dayside. The limit to mass lost to the solar wind for a thick atmosphere was taken as equal to the solar wind mass flux through the lunar cross section (~50 g·sec^{-1}), since critical mass loading of the solar wind occurs if ions are added at a rate comparable to the solar wind flow. Venus and Mars each lose about 10 g·sec^{-1} to the solar wind (*Michel*, 1971; *Cloutier et al.*, 1974; *Breus et al.*, 1989), which is 1% (Venus) and 20% (Mars) of the mass flux of the solar wind through their cross-sectional areas. The thermal escape rate for a thin exosphere in contact with the surface was calcualted with

THIN EXOSPHERE

THICK ATMOSPHERE

Fig. 7   Interactions between the solar wind and a thin atmosphere with ion pickup, and a thick atmosphere that diverts the solar wind flow.

300 K as the weighted average of the lunar surface temperature. Absorption of the solar wind and ultraviolet by a thick atmosphere results in exospheric heating and more effective thermal evaporation.

As the atmospheric density is increased, the exospheric base rises above the surface and the mass lost to thermal evaporation is no longer a constant fraction of the entire atmospheric mass. The mass loss rate is then a fraction of only the exospheric mass because the atmosphere below the exosphere does not participate in the thermal escape. The transition to a long-lived atmosphere in which thermal escape is the primary loss mechanism requires a total mass of 10^8 kg, and requires a source rate estimated to be about 60 kg·sec^{-1}. However, the surface density at this transition would still be low compared to densities in the terrestrial atmosphere. For atmospheres in excess of 10^8 kg, the atmosphere will grow if the source rate exceeds about 30 kg·sec^{-1}. For thicker atmospheres the mass loss rate depends on the escape velocity at the base of the exosphere. Therefore, the loss rate increases slowly because the exosphere rises to higher altitudes as a result of the increase in total mass.

The growth of the artificial atmosphere is ultimately limited by the large escape rate that occurs when the exosphere rises to an altitude where the thermal velocity is comparable to the escape velocity. In this case the exosphere is in a state of rapid escape, referred to as blowoff, in which the loss of gas ceases to be evaporative and becomes a hydrodynamic outflow (*Fahr and Shizgal*, 1983). The altitude at which this occurs depends on the exospheric composition and temperature. For an exosphere of atomic oxygen, the thermal and escape velocities are equal at an altitude of 13.6 lunar radii for an exospheric temperature of 400 K and 6.8 lunar radii for a temperature of 800 K. The surface densities of such extended atmospheres would greatly exceed that of the Earth. If the artificial atmosphere consisted of an atmosphere of molecular gases and a surface density equal to the Earth's atmosphere, the base of the exosphere would be at an altitude of about 3 lunar radii. In this case, the total escape rate of the exosphere (assumed to be atomic oxygen at a temperature of 700 K) would be about 60 kg/sec.

An obvious speculation is the feasibility of creating an artificial lunar atmosphere that would be "breathable" or as dense as the terrestrial surface atmosphere. Such a lunar atmosphere would have a total mass of about 2×10^{18} kg. Obtaining this much oxygen by vaporization of lunar soil requires an amount of energy equal to 5×10^{25} J, or 2×10^9 GW-yr. If nuclear devices were used, the equivalent of 2×10^{11} kt of TNT would be needed since *Ehricke* (1974) estimates that a 1-kt device will yield 10^7 kg of oxygen. Because this is approximately 10^4 times larger than the total U.S. stockpile of nuclear weapons, it seems impractical that such an amount of gas could be generated by current technology. There are no known natural gas reservoirs on the Moon, although permanently shaded regions near the lunar poles might contain as much as 10^{14} kg of condensed water (*Arnold*, 1979). Therefore, it would be necessary to import gases. For example, a cometary nucleus of radius 80 km contains 2×10^{18} kg of oxygen and could be used, in principle, to supply the man-made atmosphere.

Although the artificial generation of a lunar atmosphere can be considered as another potential method for modification of planetary environments, the desirability of intentionally increasing the density of the lunar atmosphere is highly questionable because the primary application of a lunar laboratory involves utilization of the present lunar "vacuum."
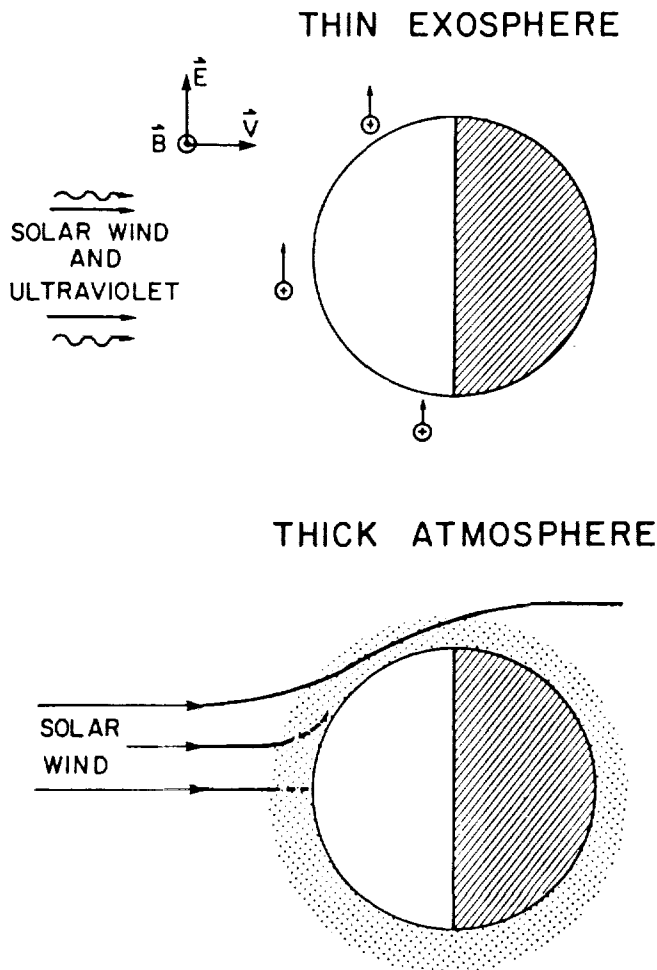
APOLLO MEASUREMENTS OF ARTIFICIAL GAS RELEASES

The Apollo database serves as a useful reference for both measurements of the natural lunar environment and its modifications by manned activities. Although no specific experiments were performed and measurements were not comprehensive, data do exist for several artificial releases such as lunar module liftoff, S-IVB impacts, and cabin vents. These data are consistent with the theoretical expectations for transient release dynamics, although some puzzles have been identified. Unfortunately, no measurements of Apollo activities were made by LACE because it was deployed on the last mission.

The lifetime of gases in the lunar atmosphere has been measured by observations of exhaust gases released into the lunar atmosphere by the Apollo vehicles. Figure 8 shows an exhaust spectrum detected by the SIDE mass analyzer soon after an Apollo landing (*Freeman et al.*, 1973). The mass distribution agrees well with laboratory measurements of the lunar module fuel combustion products. Also shown in Fig. 8 are observations of the exhaust density that were made approximately two months later. It is seen that the gas density decreases with approximately a one-month exponential decay time, consistent with the photoionization lifetime.

The Apollo 15 SIDE measured the differential fluxes of magnetosheath ions during the ascent of the Apollo 15 lunar module (*Hills et al.*, 1972). At LM ascent, a strong decrease occurred in the magnetosheath ion fluxes being detected at the time. This decrease lasted approximately eight minutes. It could be attributed to energy loss in the relatively dense exhaust gas, to losses by charge exchange, or to temporary deviations of the magnetosheath ion-flow direction caused by the exhaust gas. Full recovery of the fluxes to preascent intensities had a puzzling time-dependent variation, and variations were also seen on the ALSEP magnetometer. These could have been signatures of collective plasma phenomena or may have been results of complicated magnetosheath flow.

On April 15, 1970 the Apollo 13 S-IVB stage impacted the nighttime lunar surface approximately 140 km west of the Apollo 12 ALSEP site and 410 km west of the dawn terminator (see Fig. 9). Beginning 20 sec after impact, the SIDE and the SWS observed a large flux of positive ions (maximum flux ~3 × 10⁸ ions/cm²sec-sr) and electrons (*Lindeman et al.*, 1974). Two separate streams of ions were observed: a horizontal flux that appeared to be deflected solar wind ions and a smaller vertical flux of predominantly heavy ions (>10 amu), which were probably material vaporized from the S-IVB stage. An examination of the data shows that collisions between neutral molecules and hot electrons (50 eV) were probably an important ionization mechanism in the impact-produced neutral gas cloud. These electrons, which were detected by the SWS, are thought to have been energized in a shock front or some form of intense interaction region between the cloud and the solar wind. Thus, strong ionization and acceleration are seen under conditions approaching a collionless state. This observation indicates that plasma interactions need to be taken into account when evaluating the effects of large gas releases.

CONCLUSIONS

Although the basic features of the lunar environment were surveyed during the Apollo program, our present understanding
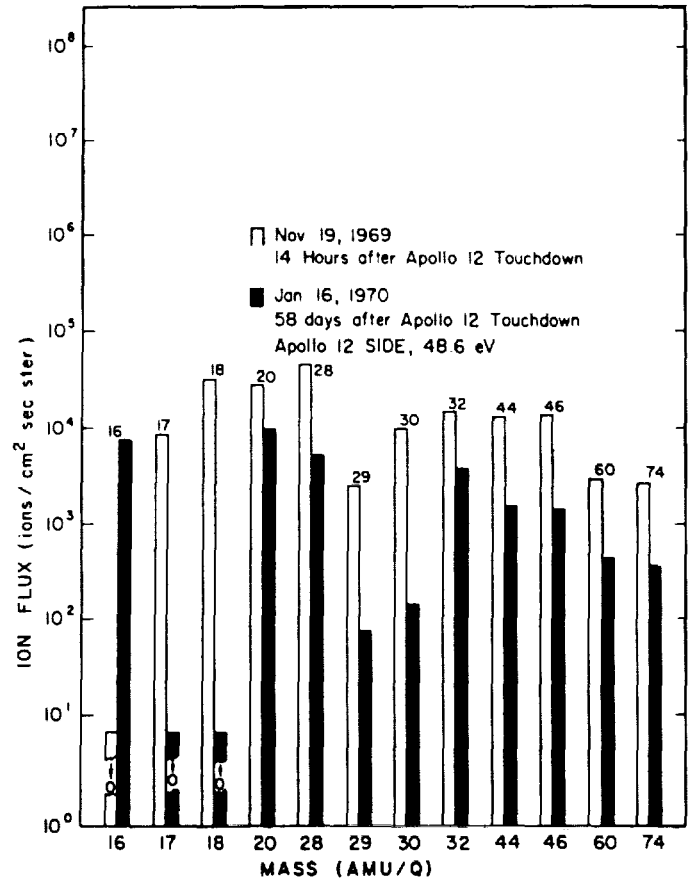

Fig. 8. Observed decrease in exhaust gas fluxes over a 58-day period (*Freeman et al.*, 1973).
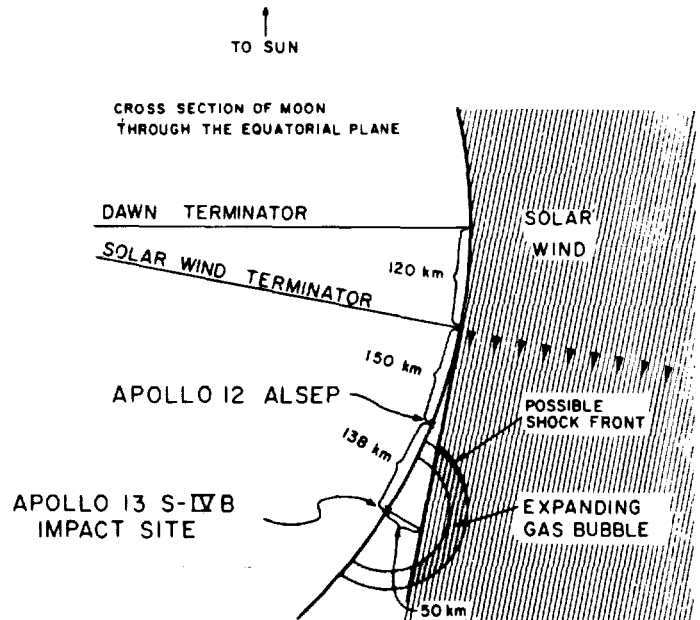

Fig. 9. An equatorial cross-sectional view of the Moon showing the location of the Apollo 13 S-IVB impact with respect to the Apollo 12 ALSEP site and the dawn and solar wind terminators (*Lindeman et al.*, 1974).

is somewhat fragmented and incomplete. The major uncertainties concern the composition and concentration of the dayside lunar atmosphere, the possible presence of transient lunar degassing, and the dynamics of the lunar ionosphere.

Based on our current understanding of the lunar atmosphere processes, small lunar bases are not expected to produce any significant long-lived alteration of the lunar atmosphere. Although the artificial gas release rate can easily exceed the natural rate, the principal effects should be both localized and transient.

Because the lunar atmosphere and ionosphere are susceptible to alteration by human activities, it is important that these be extensively surveyed prior to any lunar surface return program. In particular, measurements need to be made of the lunar atmosphere on the dayside. Also, better measurements need to be made of lunar atmospheric ions. The SIDE ion mass spectrometer had a narrow, fixed field of view and low sensitivity. Modern ion sensors can measure more completely the full three-dimensional plasma distribution with much higher sensitivity.

For astronomical applications, an important early measurement is the optical quality ("seeing conditions") at the lunar surface. Although the atmosphere is expected to be nearly transparent, there have been suggestions that dust may be present, due to measurements made by Surveyor 7, the Apollo crew, and the Lunokhod photometer (*Rozenberg*, 1970; *McCoy and Criswell*, 1974). Such measurements of atmospheric quality need to be continued after a lunar base is established, in order to monitor any alteration of the atmosphere.

Finally, the response of the lunar atmosphere to gas releases needs to be determined. Controlled releases of gases should be made, perhaps of tracer gases not naturally present in the lunar environment. Monitoring of their transport to other locations will validate our understanding of lunar environmental dynamics. Such experiments may also identify the location of any endogenous sources of volatiles. The discovery of such volatiles would greatly facilitate the establishment of a lunar base.

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