AN ARTIFICIALLY GENERATED ATMOSPHERE NEAR A LUNAR BASE

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We discuss the formation of an artificial atmosphere generated by vigorous lunar base activity in this paper. We developed an analytical, steady-state model for a lunar atmosphere based upon previous investigations of the Moon's atmosphere from Apollo. Constant gas-injection rates, ballistic trajectories, and a Maxwellian particle distribution for an oxygen-like gas are assumed. Even for the extreme case of continuous He^3 mining of the lunar regolith, we find that the lunar atmosphere would not significantly degrade astronomical observations beyond about 10 km from the mining operation.

INTRODUCTION

At present, the Moon has a tenuous, low-density atmosphere (10^5 particles/cm^3, <100 ions/cm^3) with a vacuum that is better than that in the best ground-based vacuum chambers. This atmosphere arises from impacts of solar wind particles, internal degassing, and meteoritic volatilization. Gas removal mechanisms such as thermal evaporation and solar wind electrodynamic stripping are sufficiently effective to prevent the growth of a substantial atmosphere from the natural sources of gas injection. The resulting environment is highly attractive for astronomical observations (*Burns and Mendell,* 1988) and for materials processing that requires high vacuum.

An important question to address is whether the gas and dust injected into the lunar atmosphere by exploration and colonization could overwhelm its removal and lead to a significant contamination of the lunar environment. This question was first addressed by *Vondrak* (1974) more than a decade ago. He considered the atmosphere removal rates by solar wind electrodynamic effects and thermal evaporation for a large range of atmospheric densities. He found that a long-lived "thick" atmosphere (total atmospheric mass of 10^6 kg, which is about 100 times more than at present) could form from activity generated by a vigorous lunar colony (see also *Vondrak,* 1991). This atmosphere would not dissipate for hundreds of years. It would also be optically thick to ultraviolet light, effectively rendering the lunar surface unusable for astronomy at these wavelengths.

In this paper, we present a further investigation of the artificial lunar atmosphere question. In particular, we study the growth of an atmosphere within a 200-km diameter of a lunar base. Neutral gas is injected at a constant rate, a fraction of which ionizes from solar radiation, and is allowed to evolve in time. We find that a steady state is reached with gas injection rates balancing removal rates from thermal evaporation and surface adsorption. We argue that collective plasma effects shield the atmosphere from single-particle solar wind electrodynamic forces, thus reducing ion stripping. Densities and optical depths are presented for one possible gas injection scenario.

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SOURCES AND SINKS OF GAS

Table 1 is a listing of the potential sources and sinks of gas that one might anticipate to be present in and around a thriving lunar base. The sources are described in more detail in a paper by *Taylor* (1991). The rates of gas injection are averaged over a year.

Lunar atmospheric gases are depleted by the three mechanisms listed in Table 1. Thermal evaporation occurs when the velocity of a gas particle exceeds the escape velocity of the Moon (2.4 km/sec). Thermal evaporation is not effective for particles with masses greater than He. If a gas particle has insufficient speed to escape, it will return to the Moon's surface on a parabolic ballistic trajectory (since collisions are negligible). Upon striking the surface, the gas particle may be adsorbed or re-emitted.

The solar wind flows by the Moon with an average velocity of 300 km/sec. The magnetic field embedded within the wind generates an effective electric field given by $-\vec{v} \times \vec{B}$. A single electron or ion will experience an electrodynamic force ($q\vec{E}$) that will accelerate the charged particle in a direction parallel (or antiparallel depending upon the sign of the charge) to the solar wind E-field direction. The charged particle will be quickly accelerated up to the velocity of the solar wind (within 1 Larmor period). This acceleration can be directed toward the lunar surface (at a time when the wind velocity is parallel to a tangent line of the surface at the lunar base) or parallel to the surface (when it is solar noon) in the two extremes. Thus, the wind could serve to strip charged particles out of the atmosphere and into the wind or drive them back into the surface. It is interesting to note that the acceleration of a single oxygen ion produced by the solar wind electric field is nearly 10^4 times greater than that produced by lunar gravity. *Manka and Michel* (1971) were among the first to recognize this as an important mechanism for removing gas from the lunar atmosphere.

The above scenario is applicable to situations where the density of ions is low. However, higher densities can generate important collective plasma effects that may shield the lunar atmospheric

TABLE 1. Sources and sinks of gas near a lunar base.

Sources	Rate (kg/sec)	Sink	Effectiveness
Meteoritic Volatilization	2×10^{-3}	Thermal Escape	Low to Moderate
Internal Degassing	$<3 \times 10^{-4}$	Solar Wind	Moderate
Solar Wind	5×10^{-2}	Soil Adsorption	Low to Moderate
Rocket Exhaust	10^{-2} - 10^{-1}		
Habitat Venting	5×10^{-4}		
Mining and Manufacturing			
Oxygen Production	10^{-3}		
Helium Mining	1		
Glass Production	10^{-5}		

gas from the solar wind electric field. The Debye shielding length is given by (e.g., *Chen,* 1984)

$$\lambda_D = 6.9(T/n_i)^{1/2} \text{ cm} \quad (1)$$

For ambient temperatures, T, of 300 K and densities as low as those in current lunar ionosphere ($n_i = 100$ ions cm^{-3}), λ_D is 12 cm. As shown below, the density of an artificial atmosphere is expected to be considerably larger than that of the current atmosphere near the source and thus the Debye length will also be much smaller. Thus, even using these conservative figures, solar wind electric fields will be shielded out on distances short in comparison to the scale height of the atmosphere. For neutral particle injection rates of 10^{-3} kg/sec (e.g., oxygen production in Table 1) and a solar ionization rate of 5×10^{-6} ions/atom/sec (*Freeman et al.,* 1973), there will be 2×10^{18} ions in the atmosphere within 1 sec. This will be more than adequate to produce strong plasma shielding effects.

The above analysis is applicable for a constant electric field. However, the interaction of the solar wind and charged particle gases near a lunar base is variable in time. A more appropriate quantity is the dielectric constant of the plasma given by (e.g., *Chen,* 1984)

$$\epsilon = 1 + (c/v_A)^2 \quad (2)$$

where c is the speed of light and v_A is the Alfven speed in the plasma cloud. If the embedded magnetic field is taken to be that of the solar wind (5×10^{-5} G), then the dielectric constant is $7.6 \times 10^6 n_i$. The resulting electric field that the ions will feel inside the cloud is E_{sw}/ϵ where E_{sw} is the intrinsic solar wind E-field. Thus, for all intents and purposes, the ionic gas cloud will not be affected by the external electric field.

Both the electric and magnetic fields from the solar wind will be diverted around the expanding gas cloud near a lunar base. This will produce a macroscopic pressure (Maxwell stresses of the fields) that will tend to accelerate the cloud in bulk in the direction of the solar wind. One way of describing how this momentum transfer can occur is to construct a characteristic time, t_{acc}, during which the cloud will be accelerated to the solar wind speed (*Haerendel et al.,* 1986)

$$\frac{dv_c}{dt} = \frac{v_{sw} - v_c}{\tau_{acc}} \quad (3)$$

This characteristic time is given by

$$\tau_{acc} = \frac{\rho_c l_c}{4\kappa\rho_{sw}v_A} \quad (4)$$

where ρ_c and ρ_{sw} are the cloud and solar wind densities, respectively, v_A is the solar wind Alfven speed (50 km/sec), l_c is the cloud diameter, and κ is a magnetic field compression factor on the leading edge of the cloud (generally between 5 and 20). Equation (4) can be rewritten in terms of parameters similar to those applicable to the artificial atmosphere discussed in the next section

$$\tau_{acc} = 300 \text{ yr} \left[\frac{n_c}{10^8 \text{ cm}^{-3}}\right] \left[\frac{l_c}{10 \text{ km}}\right] \left[\frac{\kappa}{10}\right]^{-1} \quad (5)$$

Thus, timescales for such bulk acceleration will be hundreds of years and, to first order, solar wind stripping is not a factor at these densities.

This collective plasma shielding was recently demonstrated to be effective in an environment similar to that on the surface of the Moon. A cloud of 2 kg of Ba vapor was released into the solar wind in 1984 and 1985 (*Valenzuela et al.,* 1986). The Ba ionized very quickly allowing the researchers to study the interaction of a highly supersonic, dilute, magnetized plasma (solar wind) with a stagnant, unmagnetized cloud. Both plasmas were collisionless. Measurements of densities, velocities, and magnetic fields demonstrated that the shielding effects discussed above became effective in <1 min. However, ion extraction produced by an antisunward-pointing polarization electric field was more effective than had been anticipated. This resulted in a smaller lifetime of the Ba plasma cloud than had been calculated.

The interaction of the solar wind with an ionized cloud is clearly more complex than simple single-particle electric field interactions that have been previously used. For the preliminary calculations that we describe below, the solar wind interactions are ignored. This results in an upper limit to the artifical atmosphere density, and thus strengthens our conclusions described below that pollution of the lunar atmosphere is not a serious problem.

FORMATION OF AN ARTIFICIAL ATMOSPHERE

We now consider a simple analytical model for the formation of an artificial lunar atmosphere. There is a large body of work that exists on the generation of atmospheres on the Moon and Mercury (e.g., *Hodges,* 1974, 1975; *Hartle and Thomas,* 1974; *Lindeman et al.,* 1974; *Potter and Morgan,* 1988). These models have been very successful in reproducing basic observations such as the gas ion flux observed by the Apollo Suprathermal Ion Detector Experiment following the impact of the Apollo 13 upper stage on the lunar surface. We have attempted to use relevant components of these previous models and apply them directly to an assessment of the effects of atmospheric modification on astronomical observations. The details of these calculations appear elsewhere (*Fernini et al.,* 1990). In this paper, we describe an overview of the model assumptions and present examples of how the lunar atmosphere will be affected by continuous mining and manufacturing near a lunar base.

We have made the following assumptions in our model calculations. First, the gas injection rate is taken to be continuous in time. This is an approximation of a scenario in which habitat venting, mining, or manufacturing processes on the lunar surface occur over long periods of time at nearly a constant rate. As is described below, this assumption leads to a steady-state atmosphere near the lunar base.

Second, the ejected gas is assumed to be collisionless. Gas particles will have ballistic trajectories through the exosphere under the lunar gravitational force. For an oxygen-type atmosphere, the mean free path is about $10^{16}n^{-1}$ cm, where n is the atmospheric density. At present, the mean free path is about 10^{11} cm. So, even for large increases in atmospheric density, the atmosphere is expected to remain collisionless.

Third, only a neutral atmosphere is considered. Nonthermal escape mechanisms such as photoionization and removal by the solar wind are neglected. This will be true near the source where the plasma shielding is most effective. However, further out where the density drops, electrodynamic stripping by the solar wind electric field will become important. Thus, our model represents an upper limit to the expected atmospheric density.

Fourth, the gravitational acceleration is assumed to be constant (i.e., flat Moon approximation). This approximation has been used extensively in past models (e.g., *Hodges,* 1972; *Lindeman et al.,* 1974) where localized sources of gas have been considered. Within the volume surrounding the lunar base that we consider (a box centered on the gas source with dimensions of 200 km along the lunar surface and an altitude of 100 km), the real gravitational acceleration of the Moon is within 10% of the constant value of 1.62 m/sec^2 that we assume. *Hodges and Johnson* (1968) have shown that this assumption limits the applicability of results to gases with smaller scale heights; however, this limitation affects only lunar hydrogen and helium. Since an oxygen-like atmosphere is the only one being considered in our models, we believe that this approximation is reasonable. We emphasize here that we are only interested in the atmospheric conditions near a lunar base. Thus, the model predictions are limited to the vicinity of the base.

Fifth, the particle distribution is Maxwellian characterized by the source or surface temperature. The particles are also assumed to have initially isotropic trajectories. For our models, the temperature is assumed to be constant in the calculation.

In our model calculations, we considered two types of gas transport. The first, which we term direct transport, involves simple direct flux transport of particles released from a point source on the lunar surface. The particles are assumed to be premanently adsorbed by the surface on the first contact. Here we follow the techniques outlined by *Hodges et al.* (1972) and *Lindeman et al.* (1974). In this model, the rate of atmosphere growth increases precipitously for the first few seconds, levels off, then sharply drops toward zero. This implies that a steady-state balance is reached between the rate of particle injection and particle loss through adsorption and escape from our grid. This equilibrium is reached about 20 minutes after the source is turned on. (Since the gas is collisionless, this timescale is independent of gas injection rate.)

The second transport mechanism is termed diffusion. In this model, the particles are allowed to "bounce" off the surface an indefinite number of times. Since the adsorption lifetime of an oxygen-like molecule is short ($<10^{-2}$ sec at T = 100 K), repeated bounces of a given molecule into the atmosphere are likely. *Hall* (1973) recognized this process on the Moon to be similar to a one-dimensional diffusion problem as originally described by *Chandrasekhar* (1943). We assume that upon adsorption, the particle is immediately re-emitted isotropically at a temperature characteristic of the lunar surface.

We find that for moderate mass molecules (i.e., oxygen) and for small distances from the injection point (<20 km), direct transport is the dominant process at T = 100 K. For higher temperatures, direct transport dominates out to larger distances (e.g., 50 km for T = 300 K). For larger distances, smaller temperatures, and heavier molecules, diffusion dominates. So, for a complete model of an artificial atmosphere, one must consider both transport processes.

DISCUSSION

We now apply the above models to a particular gas injection scenario. We choose the most extreme example of which we are aware, namely that of helium production (*Wittenberg et al.,* 1986). In this scenario, large amounts of regolith must be mined to obtain enough helium for fusion energy back on Earth. The rate listed in Table 1 assumes that 10% of the gas in the mining process is lost to the atmosphere. This produces an injection rate of 2×10^{25} part/sec. For this example, we also consider the outgassing to consist of molecular oxygen (although a range of other gas products is expected, oxygen is representative) and the surface/source temperature to be 100 K (lunar night).

In Table 2, we list the gas density, column density (approximated as the nH where H is the atmospheric scale height, which is 30 km for O_2 at 100 K), and optical depth at ultraviolet wavelengths for three distances from the source, 1 km, 5 km, and 60 km. It is clear from Table 2 that beyond a few to 10 km from a lunar base, the atmosphere will be significantly denser than at present, but it remains sufficiently transparent to conduct optical/ultraviolet astronomy.

We also list in Table 2 the plasma frequency of the lunar ionosphere for the above model. We have roughly estimated the density of ions/electrons in the atmosphere by assuming a constant rate of ionization from solar photons, 5×10^{-6} ions/atom/sec (e.g., *Freeman et al.,* 1973). The density of the ionosphere will determine the minimum frequency for radio observations from the surface. The ionosphere will reflect radio waves with frequencies less than $9n_e^{1/2}$ kHz. For densities $>10^4$ electrons/cm^3, the ionosphere will not transmit radio waves with frequencies below 1 MHz. This is a crucial wavelength window for radio astronomical observations from the lunar farside (*Douglas and Smith,* 1985). It would appear, then, that a very low frequency radio astronomy observatory should be located beyond about 5 km from the helium production facility.

CONCLUSIONS

Our analysis of the growth of an artificial lunar atmosphere suggests that the astronomical environment beyond about 10 km from mining or manufacturing operations will be relatively unaffected by the resulting outgassing. The transparency of the atmosphere remains high for very low frequencies and ultraviolet wavelengths.

We believe that our simple atmospheric models are reasonable order-of-magnitude estimates of the lunar gas densities. In the limits of smaller injection rates, our models agree very well with measurements from Apollo experiments. However, our models are only approximations since we have made several simplifying assumptions including constant source/surface temperatures and no losses due to stripping by the solar wind. The latter, however, can only strengthen our conclusion.

Our models are also limited to the direct vicinity of a lunar base. We have not considered global additive effects such as multiple mining operations. These collective effects could potentially increase the overall atmospheric density, but this appears unlikely unless there are large numbers of such facilities with increased outgassing as assumed by *Vondrak* (1974). According to our models, each such facility is ineffective near the boundaries of our grid, with outer densities nearly equal to that of the current atmospheric density. Diffusion of gas between the individual sites and around the Moon is not likely to be important since solar wind stripping becomes more effective for longer particle lifetimes (greater probability of ionization) and at lower densities (less shielding by collective plasma effects). This process has been effective in the past in keeping the lunar atmospheric density low in spite of multiple sites of meteoritic volatilization.

In summary, it appears that a vigorous lunar base will not impede astronomical observations from the lunar surface. Our conclusions can be tested quantitatively by gas release experiments during lunar precursor or early lunar base missions.

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REFERENCES

Burns J. O. and Mendell W. W., eds. (1988) *Future Astronomical Observatories on the Moon.* NASA CP-2489. 134 pp.

Chandrasekhar S. (1943) Stochastic problems in physics and astronomy. *Rev. Mod. Phys., 15,* 1-89.

Chen F. F. (1984) *Plasma Physics and Controlled Fusion,* 2nd edition. Plenum Press, New York. 421 pp.

Douglas J. N. and Smith H. J. (1985) A very low frequency radio astronomy observatory on the Moon. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 301-306. Lunar and Planetary Institute, Houston.

Fernini I., Burns J., Taylor J., Sulkanen M., Duric N., and Johnson S. (1990) Disposal of gases generated near a lunar outpost. *J. Spacecr. Rockets, 27,* 527-538.

Freeman J. W., Hills H. K., Lindeman R. A., and Vondrak R. R. (1973) Observations of water vapor ions at the lunar surface. *Moon, 8,* 115-128.

Haerendel G., Paschmann G., Baumjohann W., and Carlson C. W. (1986) Dynamics of the AMPTE artificial comet. *Nature, 320,* 720.

Hall F. G. (1973) Role of pressure transients in the detection and identification of lunar surface gas sources. *J. Geophys. Res., 78,* 2111-2132.

Hartle R. E. and Thomas G. E. (1974) Neutral and ion exosphere models for lunar hydrogen and helium. *J. Geophys. Res., 79,* 1519-1526.

Hodges R. R. (1972) Response of lunar atmosphere to volcanic gas releases. *Planet. Space Sci., 20,* 1849-1864.

Hodges R. R. (1974) Model atmospheres for Mercury based on a lunar analogy. *J. Geophys. Res., 79,* 2881.

Hodges R. R. (1975) Formation of the lunar atmosphere. *Moon, 14,* 139.

Hodges R. R. and Johnson F. S. (1968) Lateral transport in planetary exospheres. *J. Geophys. Res., 73,* 7307.

Hodges R. R., Hoffman J. H., Yeh T. T. J., and Chang G. K. (1972) Orbital search for lunar volcanism. *J. Geophys. Res., 77,* 4079-4085.

Lindeman R. A., Vondrak R. R., Freeman J. W., and Snyder C. W. (1974) The interaction between an impact-produced neutral gas cloud and the solar wind at the lunar surface. *J. Geophys. Res., 79,* 2287-2296.

Manka R. H. and Michel F. C. (1971) Lunar atmosphere as a source of lunar surface elements. *Proc. Lunar Sci. Conf. 2nd,* pp. 1717-1728.

Potter A. E. and Morgan T. H. (1988) Discovery of sodium and potassium vapor in the atmosphere of the Moon. *Science, 241,* 675-680.

Taylor G. J. (1992) Astronomy on the Moon: Geological considerations. In *The Second Conference on Lunar Bases and Space Activities of the 21st Century,* this volume.

Valenzuela A., Haerendel G., Föppl H., Melzner F., Neuss H., Rieger E., Stöcker J., Bauer O., Höffner H., and Loidl J. (1986) The AMPTE artificial comet experiments. *Nature, 320,* 700-703.

Vondrak R. R. (1974) Creation of an artificial lunar atmosphere. *Nature, 248,* 657-659.

Vondrak R. R. (1992) Lunar base activities and the lunar environment. In *The Second Conference on Lunar Bases and Space Activities of the 21st Century,* this volume.

Wittenberg L. J., Santarius J. F., and Kulcinski G. L. (1986) Lunar source of ^{3}He for commercial fusion power. *Fusion Technol., 10,* 167.