**IS THE MOON REALLY A SURFACE-BOUNDED EXOSPHERE?** T. A. Livengood[1] and D. R. Williams[2], [1]Dept. of Astronomy U. of Maryland, College Park, MD 20742, tlivengo@umd.edu, [2]Solar System Exploration Division, NASA Goddard Space Flight Center, Greenbelt, MD 20771, david.r.williams@nasa.gov.

It is commonly accepted that the lunar surface environment is a surface-bounded exosphere, nearly pure vacuum. This designation follows from a theoretical argument that predicts the photolysis of likely atmospheric molecules and the escape to space of photolysis products and low-mass atomic gases, given the Moon's low gravity and relatively warm dayside surface temperatures. Empirical support for this theoretical prediction is remarkably scant. Several recent measurements are in conflict with predictions for the density of a lunar surface-bounded exosphere, implying that the lunar atmosphere is denser and more complex than an exosphere.

The physics of exospheres is described by Chamberlain and Hunten [1]. The exosphere is the region above the exobase, the altitude above which the mean free path of particles in an atmosphere is comparable to or greater than the pressure scale height, $H = kT/mg$, for exponential decline with altitude. In a surface-bounded exosphere, the exobase is at the surface and the surface temperature defines the temperature, $T$, in the scale height. The mass, $m$, is the mass of individual gas particles, $g$ is the local gravitational acceleration, and $k$ is the Boltzmann constant. Species within an exosphere are not in local thermodynamic equilibrium (LTE), since a molecule or atom that launches from the exobase due to thermal motion is likely to radiate its internal energy long before it escapes to space or ballistically returns to the surface without encountering another particle during its flight.

If the exobase temperature is sufficient that the translational speed of a species is a significant fraction of escape velocity (approximately $>1/6^{th}$), then that species is likely to be depleted by escape to space. Escape velocity from the Moon is about 2.4 km/s. Translational speed (rms) is $v_{rms} = \sqrt{3kT/m}$ = 1.6 km/s at 100K for one nucleon; this is the speed for atomic hydrogen at lunar nighttime surface temperature [2]. Translational speed for other species and other temperatures can be scaled up by square root of temperature in 100K units and down by square root of nuclear mass in number of nucleons. For a water molecule at typical noon temperature, $v_{rms}$ = 1.6 km/s • $(4/18)^{1/2}$ = 0.74 km/s. This is great enough to imply direct escape to space if the Moon's surface were the exobase. All molecular species common in Earth's atmosphere ($H_2O$, $N_2$, $O_2$, $CO_2$) are capable of escape from the lunar exobase at noon surface temperature of just less than 400K, whereas none could escape at pre-dawn temperature, 100K.

The Apollo crewed missions to the lunar surface deployed seven instruments that attempted to measure pressure in the lunar atmosphere: a cold-cathode ion gage (CCGE or CCIG) on each of Apollo 12, 14, and 15; a suprathermal ion detector (SIDE) on each of the same missions; and a mass spectrometer, the Lunar Atmosphere Composition Experiment (LACE) on Apollo 17. These experiments are reviewed by Stern [3] and individually described at respective pages of the National Space Science Data Center.

No experiment successfully measured the dayside neutral atmosphere, although most were operated at nighttime for months or years after deployment. The Apollo 12 CCGE measured a minimum pressure of ~0.01 nanobar (nbar) before failing. At ~300K during Apollo landed operations, this corresponds to a number density of $\sim 3 \times 10^8$ mol/cm$^3$, an order of magnitude greater than exospheric density. Some daytime data acquired with the Apollo 14 CCGE is suspiciously steady and noise-free, suggesting that the instrument had reached a hard stop and reported false measurements. The Apollo 15 CCIG failed early and returned highly variable data that could not be quantified. Relatively low ion densities measured by SIDE were consistent with low atmospheric density – even as the CCGE experiments measured local densities a few orders of magnitude greater. A common theme in the data reports is that the CCGE and SIDE experiments were commanded off during most of the lunar day due to repeated incidents of overheating or arcing, suggesting untrustworthy performance at all times of lunar daylight.

LACE operated successfully only at night [4], measuring helium, neon, and argon monatomic gases. Approaching dawn, various mass numbers appeared and grew in number, corresponding to simple molecules such as water, $N_2$ or CO, $CH_4$, and so forth. As daylight reached the instrument, LACE saturated on each of 10 lunar dawns before instrument failure. Hoffman and Hodges [4] state that the maximum daytime atmosphere could be no more than $\sim 10^7$ mol/cm$^3$, cited by Stern [3] as an upper limit. In fact, this is the predicted upper limit for the exobase, not an empirical measurement.

In recent years, hydrated minerals on the lunar surface have been reported from near-IR and UV reflec-

tance spectroscopy [5,6,7,8]. In addition, neutron flux measurements from the Lunar Reconnaissance Orbiter (LRO) have shown diurnal variation, consistent with hydrogen-bearing volatiles concentrated near the dawn terminator [9]. The implied hydrogen density at dawn, averaged over the whole equatorial band, implies an average surface density of about $10^{20}$ mol/cm$^2$, assuming two H atoms per molecule. About 99% of molecules would be sequestered within the surface before desorption and rapid horizontal migration across the dawn terminator to recondense on the cold nighttime surface, leaving about $10^{18}$ mol/cm$^2$ average in free space above the surface. Distributing this quantity over a column about 10 km height yields a near-surface volume density of about $10^{12}$ mol/cm$^3$, five orders of magnitude greater than an exobase.

The minimum thickness of a detectable mineral hydrate layer for NIR reflectance measurements would be a rind on soil grains of about one micron. Although these measurements are poorly quantified, they imply a number density of about $5 \times 10^{13}$ mol/cm$^2$ above the surface to form a diurnally transported population seen by Sunshine *et al.* [6], implying a volume density over 10 km of about $5 \times 10^7$ mol/cm$^3$ – comparable to the predicted exosphere on average. If the adsorbed layer were a millimeter thick rather than a micron, the concentration of the atmosphere would exceed exobase density by about three orders of magnitude.

At some altitude above the surface, the atmosphere would become sufficiently tenuous to form an exobase. The atmosphere would be convectively heated from below and thus temperature would decrease with altitude. Water, methane, ammonia, and any other hydrogen-bearing volatile apart from $H_2$, also have the important property that they are infrared active. In a collisional atmosphere molecules are in LTE and thus balance impact excitation against radiative cooling to space, decreasing the temperature more rapidly with altitude than the adiabatic lapse rate due to convection, drastically shortening the scale height: a surface-bounded mesosphere. In Earth's convectively supported and radiatively inefficient $N_2$ and $O_2$ atmosphere, $H_2O$ nevertheless cools sufficiently to form liquid and ice aerosol clouds at ~2 km altitude. Scaling by reduced gravity on the Moon suggests that ice clouds would form at ~12 km maximum, probably much lower due to the steeper lapse rate. A snow layer would form as a roof supported by the collisional atmosphere below. Methane and ammonia do not condense at temperatures found in sunlight at ~1 AU. The lack of noticeable drag on lunar spacecraft implies that these species are not significant in the lunar atmosphere, which would thus be exclusively water. For monatom-

ic species with very small collision cross-sections, the exobase would still be at the surface due to diffusive separation from the molecular gas.

The Moon's morning sector, in which neutron detection implies significant hydrogen, thus appears to feature a water-dominated collisional atmosphere.

Despite relatively cold radiative equilibrium temperatures in the snow layer that would form the actual exobase (~170K), ongoing photolysis and thermal escape imply the loss of the atmosphere to space over geologic time despite self-shielding of most of the atmosphere [10]. New hydrogen is delivered to the Moon by the solar wind, and both water and other volatile species are delivered steadily by micrometeoroid impacts. Both delivery rates are quite small and would require highly effective self-shielding against photolysis and retention of photolysis products. A less bold assumption for the effectiveness of self-shielding requires a larger supply rate than exogenous mechanisms can account for. An indigenous supply of water could maintain equilibrium through outgassing from a primordial inventory within the Moon's crust and mantle.

Relatively rapid resupply of water from outgassing implies a D/H ratio in the current atmosphere similar to Earth's, as the Moon's volatile inventory, like the Moon's solid matter, would be derived from the Earth's primordial crust and upper mantle. Deuterium would be slightly enriched, since H and D as well as $H_2O$ and HDO are capable of being lost to space from the exobase. If the current atmosphere were maintained in equilibrium with the slow processes of solar wind delivery and micrometeoroid impact, then the D/H ratio would be highly enriched in deuterium relative to Earth. The measured D/H ratio in escaping gases, measured in near-lunar space, could address the D/H ratio of the current atmosphere. The most valuable empirical observation would be to finally measure the Moon's real diurnally varying atmosphere, *in situ*, with sufficient dynamic range to obtain both day and night composition and pressure.

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