

**The Lunar Atmosphere:  
History, Status, Current Problems, and Context**

**S. Alan Stern  
Space Studies Department  
Southwest Research Institute**

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Send correspondence to:

Alan Stern  
Southwest Research Institute  
1050 Walnut St., No. 426  
Boulder, CO 80302

[astern@swri.edu](mailto:astern@swri.edu)

[303]546-9670 (voice)

[303]546-9687 (fax)

## ABSTRACT

After decades of speculation and fruitless searches by observers, the lunar atmosphere was first observed by Apollo surface and orbital instruments beginning in 1973. With the end of Apollo missions in 1972, and the termination of funding for Apollo lunar ground station observations in 1977, the field withered for many years, but has recently enjoyed a renaissance. This renewal was initiated by the discovery of lunar atmospheric sodium and potassium by groundbased observers, and furthered by the *in situ* detection of metal ions derived from the Moon in interplanetary space, the possible discoveries of H<sub>2</sub>O ice at the poles of the Moon and Mercury, and the detection of tenuous atmospheres around other remote sites in the solar system, including Mercury and several Galilean satellites. In this review I attempt to summarize the present state of knowledge about the lunar atmosphere, describe the important physical processes taking place within it, and provide a comparison of the lunar atmosphere to other tenuous atmospheres in the solar system.

## 1.0 OVERVIEW

Owing to the lack of optical phenomena associated with the lunar atmosphere, it is usually stated that the Moon has no atmosphere. This is not correct. In fact, the Moon is surrounded by a tenuous envelope with a surface number density and pressure not unlike that of a cometary coma.<sup>[1]</sup> Since the lunar atmosphere is in fact an exosphere,<sup>[2]</sup> one can think of its various compositional components as “independent atmospheres” occupying the same space.

This review is structured as follows: In §1 I will describe the history and provide an overview of the current state of knowledge about the lunar atmosphere. In §2 I discuss the structure and dynamics of the lunar atmosphere. In §3 I provide a more detailed look at the production and loss mechanisms of the lunar atmosphere. In §4 I provide a comparison of the lunar atmosphere to tenuous exospheres around other bodies in the solar system, with particular emphasis on comparison to Mercury. In §5, we examine some special topics, including some comments on both the ancient lunar atmosphere and human influences that may occur in the future. Finally, in §6, I summarize the major outstanding issues concerning lunar atmospheric science, and briefly describe some important experiments that could shed more light on this tenuous but fascinating aspect of Earth’s nearest neighbor.

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<sup>[1]</sup> However, the analogy ends there: The lunar atmosphere is essentially everywhere collisionless, unlike a cometary coma, its composition is quite different from that of any comet, and the extant lunar species do not create optically bright emissions.

<sup>[2]</sup> In which particle-particle collisions are rare.

Before beginning, I caution the reader that this review could not possibly cover every topic relating to the lunar atmosphere in the depth it deserves, and tough choices had to be made about both the breadth and depth of the discussions that follow. Any deficiencies in this approach are the responsibility of this author.

## 1.1 A Brief Pre-Apollo History of Quantitative Atmospheric Searches

Although the lunar atmosphere was not detected until the Apollo era, scientifically based searches for it extend back to telescopic observations by Galileo. Based on the fact that optical phenomena like hazes, refraction, and clouds were not detectable, even with primitive instruments, it was known for centuries that the lunar atmosphere must be extremely tenuous, at best.

Limiting the discussion here to only key work done in this century, the record of successively more constraining research results can be defined as follows: Fessenkov [1943] reported a search for polarization effects near the lunar terminator to set an upper limit near  $10^{-4}$  bars on the surface (i.e., base) pressure of the lunar atmosphere.<sup>[3]</sup> Using a Lyot polarimeter, Dollfus [1952, 1956] later reported successive upper limit pressures of  $\approx 10^{-9}$  bars and  $\approx 10^{-10}$  bars, respectively. And during the early space age, theorists developed a convincing case that any ancient lunar atmosphere or plausible present-day source would have been rapidly lost to space through nonthermal loss processes, including blowoff, charge exchange, photoionization, and solar-wind scavenging (e.g., Herring and Licht, [1959]; Singer [1961]; Hinton and Taesch, [1964]).

Later, occultation tests searching for the refraction of radio signals from spacecraft (e.g., Pioneer VII) and radio stars were eventually able to set an upper limit of  $40 \text{ e}^- \text{ cm}^{-3}$  on the bulk near-Moon ion density [Pomalaza-Diaz, 1967]. Johnson [1971] coupled these data with a model of the expected ionization fraction of the lunar atmosphere to set several species-dependent surface pressure limits, including  $\sim 3 \times 10^{-9}$  bars for hydrogen,  $\sim 8 \times 10^{-10}$  bars for He, and  $\sim 8 \times 10^{-12}$  bars for Ar. Limits like these were the state of the art until Apollo instruments were flown to the Moon to make more sensitive searches.

## 1.2 Lunar Transient Phenomena

In addition to the kinds of searches described above in §1.1, there has, particularly in the latter half of the twentieth century, been an ongoing effort to search for evidence of sporadic outgassing from the Moon. Such outgassing is termed “Lunar Transient Phenomena” (LTP), which I briefly discuss here. Despite the fact that no definitive data set exists to verify LTP reports (e.g., a two-site image series or simultaneous images and spectra), a sig-

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<sup>[3]</sup> A conversion of bars to concentration can be made from the perfect gas law, yielding  $n=2.61 \times 10^{19} (\text{T}/300 \text{ K})^{-1} \text{ cm}^{-3}$ .

nificant number of lunar observers regard LTP as real, and a manifestation of atmospheric activity.

There is a long history of documented reports (stretching back to at least 557 B.C.; see Middlehurst [1967]) of groundbased sightings of discrete LTP. In the modern era, interest in LTP was dramatically enhanced by (i), 1955 Mt. Wilson patrol images which apparently showed luminescent areas on or over the crater Alphonsus, and (ii) Kozyrev's November 1958 spectrographic sequence showing a transient spectral emission from the central peak of Alphonsus [Kozyrev, 1959, 1962].<sup>[4]</sup>

Both Middlehurst [1967] and later Cameron [1972, 1975, 1978] made in-depth studies of hundreds of reported LTP events. They found that two-thirds of the reported events occurred over the crater Aristarchus, a site where the orbiting Apollo 16 Command Service Module (CSM) later detected radon emission. The lack of a sufficiently systematic patrol for LTP makes statistical testing of the phenomenon difficult. Still, Cameron [1972, 1974] demonstrated that although no statistically significant correlations of reported events occur with lunar phase or solar wind activity, the geographical distribution of LTP sites appears to be correlated with mare/highland boundaries.<sup>[5]</sup> In the 1990s, Buratti & McConnochie [1999] used Clementine mission imagery to study seven sites where LTP reportedly have clustered, and found several of these locales to be associated with geologically recent landslides or downslope slumping.

### 1.3 Apollo Observations of the Lunar Ionosphere

Observations of ions in the lunar environment were carried out beginning in late, 1969 and extending to, 1977 by the three surface-based Suprathermal Ion Detector Experiments (SIDE) emplaced by Apollos 12, 14, and 15, and the Charged Particle Lunar Environment Experiment (CPLEE) emplaced by Apollo 14.

Each SIDE instrument [Freeman, 1972] consisted of a mass analyzer (measuring six mass-to-charge ( $m/q$ ) bands from 0.2 eV/ $q$  to 48.6 eV/ $q$ ) and a total ion detector (measuring 20  $m/q$  bands from 0.01 KeV/ $q$  to 3.5 KeV/ $q$ ). A key operating aspect of this device was that it could only detect ions entering its relatively narrow,  $6\times 6$  deg field of view. The instrument field of view was aligned north-south and set to view 15 deg from the local vertical. Because ions from the lunar atmosphere are highly directional, SIDE could therefore only measure them occasionally, when the solar wind magnetic field was aligned north-south (this occurred primarily only near terminator crossings).

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<sup>[4]</sup> Kozyrev attributed this emission to  $\sim 4\times 10^{12}$  g of C<sub>2</sub> fluorescing in sunlight, a very large amount, which many workers call into question.

<sup>[5]</sup> This is an intriguing conclusion, owing to the Apollo 15 and 16 Rn gas detections which were also correlated with mare/highland boundaries, as I describe in §1.3.

The goals of the SIDE experiment were to detect and characterize ions created from lunar atmosphere neutrals, ions in the solar wind as they interacted with the Moon, and the strength of the lunar surface electric field. As described by Benson et al. [1975], SIDE observations detected lunar atmosphere-generated ions, solar wind (and even terrestrial, planetary wind) ions, ions created by various Apollo spacecraft and debris sources, and ions time correlated with seismic detector signals that were later attributed to meteoroid impacts. Almost all of these signatures were detected during the lunar day.<sup>[6]</sup> The SIDE instruments also measured near-surface dayside electric potentials of +5 to +10 V, and nightside potentials of -10s to -100s of V; a Debye screening length of  $\lambda=1$  km was derived.

Based on the results obtained by the SIDE instruments, it was learned that the lunar ionosphere is directly coupled to the interplanetary electric field. As a result, ion fluxes are nonthermal, highly directional, and quite variable. As in the neutral lunar atmosphere, interactions with the lunar surface control the chemistry, and atmospheric (i.e., ion) collisions are rare. Very near the surface a dayside photoelectron sheath of height a few  $10^2$  m and a density of order  $10^4$   $\text{cm}^{-3}$  exists [Reasoner and Burke, 1972]. Above this layer is a deep region of ions whose source is the neutral lunar atmosphere. Once formed, these ions are driven either toward (i.e., into) or away from the Moon as they are accelerated along interplanetary electric field lines; Figure 1.1 details some aspects of the lunar ionosphere.

Concerning ionized gas detections, all three SIDE instruments routinely detected  $m/q=20$  to  $m/q=28$  and  $m/q=40$  to  $m/q=44$  ions generated by  $V \times B$  drift into the instrument apertures around times of local terminator surface crossings. These signals, with typical fluxes of  $\sim 10^5$   $\text{cm}^{-2}$   $\text{s}^{-1}$   $\text{sr}^{-1}$  were attributed to ionized  $^{20}\text{Ne}$  and  $^{40}\text{Ar}$  from the native lunar atmosphere (see §1.4). Benson et al. [1975] and Freeman and Benson [1977] found that a neutral gas source of roughly  $10^5$   $\text{cm}^{-3}$  Ar atoms would be required to explain the  $m/q=40$  to  $m/q=44$  ions they detected; this result is consistent with Apollo 17 site neutral mass spectrometer measurements of neutral Ar around sunrise (again, see §1.5). Assuming an Ar composition, the SIDE data imply an exponential atmosphere with a barometric (i.e., thermal) scale height near 40 km. Since no direct observation of neutral Ne atoms has ever been made, the  $^{20}\text{Ne}$  inference from SIDE data has been largely ignored in subsequent literature.

Despite the fact that ions generated from the neutral atmosphere were so often observed at terminator crossings, only one possible sporadic gas emission event was observed during the lunar daytime. The lack of additional events significantly constrains the lunar internal outgassing rate. Vondrak [1974] used the lack of SIDE-detectable gas transients, with an

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<sup>[6]</sup> Although ion outbursts were detected during the lunar night with fluxes of  $\sim 10^4$   $\text{cm}^{-2}$   $\text{s}^{-1}$   $\text{sr}^{-1}$  and  $m/q < 10$  eV/amu, such events were attributable to solar wind ions transported into the SIDE field of view by fluid turbulence effects.

equivalent neutral gas detection threshold near  $3 \times 10^{-10}$  g cm<sup>-2</sup> (or  $0.5\text{--}2 \times 10^{-12}$  molecules cm<sup>-2</sup>), to eliminate the possibility of any discrete gas release events of magnitude larger than a few  $10^7$  g on the lunar front side during the period of SIDE operations. Vondrak [1977] noted that the SIDE event detection threshold should have been capable of detecting the November 1958 Kozyrev LTP event at Alphonsus.

The single, exceptional event detected by SIDE investigators was the 14-hour-long, post-sunrise event of 7 March, 1971 observed by the Apollo 14 SIDE. This event occurred shortly after the first sunrise at the Apollo 14 site after the instrument was emplaced; it was never repeated. The 7 March, 1971 event signature displayed a complex time history of water vapor ions. Although it was initially attributed to a possible indigenous lunar source [Freeman et al., 1973]; Freeman and Hills [1991] later concluded that the most probable source of these water ions was Lunar Module (LM)— derived water evolving out of the local regolith as it warmed after sunrise. Accordingly, this well-known event is now generally accepted to be an exploration-generated, as opposed to an indigenous lunar event.<sup>[7]</sup>

#### 1.4 Apollo Observations of the Neutral Lunar Atmosphere

As a part of the Apollo lunar science program, three Cold Cathode Gauge Experiments (CCGEs) and a mass spectrometer (called LACE) were deployed on the lunar surface. Additionally, two mass spectrometers, two alpha particle spectrometers, and an ultraviolet (UV) spectrometer were placed in orbit for brief periods during, 1971–1972. These instruments were designed to measure various compositional and bulk properties of the neutral lunar atmosphere. I begin this subsection with a review of the results of the surface instruments in this suite, and then proceed on to the results obtained by the orbital instruments.

Cold Cathode Gauges were emplaced on the lunar surface at the Apollo 12, 14, and 15 sites in December 1969, January 1971, and July 1971, respectively. These devices were capable of measuring total atmospheric pressure. The Apollo 12 instrument failed after less than 1 day of operation, but the Apollo 14 and 15 instruments operated until the mid-1970s.

Contamination in the area of the Apollo surface detectors and outgassing from the instrument’s interior severely constrained each CCGE’s ability to make good measurements during the lunar daytime. As a result, the CCGEs determined only weak upper bounds of  $2 \times 10^7$  molecules cm<sup>-3</sup> in the local daytime environment as the instrument saturated near sunrise. However, during the cold lunar night when outgassing from equipment was not a

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<sup>[7]</sup> Although Freeman and Hill’s arguments concerning the probable cause of the 7 March, 1971 Apollo 14 SIDE event are well taken, one should point out that no similar post-landing events were detected by the Apollo 12 and 15 SIDE instruments.

significant factor, CCGEs clearly detected the nighttime lunar atmosphere. Because the derived densities were dependent on the (then) unknown composition of the atmosphere, investigators quoted densities for the assumption of  $\text{N}_2$  gas; this resulted in a derived  $2 \times 10^5$  molecules  $\text{cm}^{-3}$  at night, with factor of 2 uncertainties owing to the true composition.

As noted above, the final Apollo mission, Apollo 17, also deployed the LACE mass spectrometer on the lunar surface. This instrument had a mass range of 1–110 amu, and a sensitivity of 1 count  $\text{s}^{-1}$  (equivalent to  $\approx 200 \text{ cm}^{-3}$ ). Unfortunately, LACE failed only 9 months into a planned two-year study. Like the CCGEs that preceded it, LACE was routinely swamped by artifacts emanating from the nearby LM descent stage and other abandoned equipment during the lunar daytime [Hoffman et al., 1973]. However, LACE obtained firm detections of two species, argon and helium, during the lunar night.<sup>[8]</sup> Initial reports of daytime  $^{20}\text{Ne}$  detection by LACE were later revealed to be consistent with a contamination source of  $\text{H}_2^{18}\text{O}$  from Apollo equipment [Hodges et al., 1973]. Possible pre-sunrise detections of other species were also obtained. I now describe each LACE signature, in turn.

Argon, which is adsorbable on the cold-trapped ( $\sim 100 \text{ K}$ ) lunar nighttime surface was observed to follow a diurnal pattern with a night time minimum near  $2 \times 10^2 \text{ cm}^{-3}$ , followed by a rapid increase around sunrise to values as high as  $3 \times 10^4 \text{ cm}^{-3}$  before LACE became saturated by gas evolving off the warming lunar surface [Hodges et al., 1972a]; this is shown in Figure 1.2. The identification of Ar as lunar was based on the fact that the typical  $^{40}\text{Ar}:^{36}\text{Ar}$  ratio was found to be 10:1, far different from the  $^{40}\text{Ar}:^{36}\text{Ar} \ll 1$  ratio of the solar wind; the dominant lunar Ar source (like the terrestrial source),  $^{40}\text{Ar}$ , results from the decay of  $^{40}\text{K}$ .

Hodges et al. [1973] reported evidence for a time-variable lunar  $^{40}\text{Ar}$  source of  $1\text{--}4 \times 10^{21} \text{ s}^{-1}$ , which was attributed to possible indications of a variable release rate from the deep interior.

Recently, Flynn [1998] claimed a  $3\sigma$  detection of the neutral lunar Ar 1048 Å emission line. These data were collected using the Orfeus-Spas satellite to make observations in Earth orbit during December 1996. The somewhat weaker 1067 Å Ar I emission line was not detected in these observations. If verified, this would represent both the first detection of lunar Ar by remote sensing, and the first daytime measurement of lunar Ar. However, it has been criticized by Parker et al. [1998, 1999] on the grounds that for much of the plausible temperature range one should expect for Ar in the lunar atmosphere, Flynn’s optically thin analysis of the feature attributed to Ar is invalid, and an optically thick treatment yields an Ar column significantly exceeding that of the entire lunar atmosphere. The high

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[8] The  $^{40}\text{Ar}$  detected by LACE had been predicted to exist based on excess Ar embedded in lunar samples [Manka and Michel, 1970].



Ar column published in Flynn [1998] has also been criticized by Hodges [pers. comm. 1998] on the grounds that it implies an untenable Ar escape rate from the lunar interior and is incompatible with the existence of a lunar core. Flynn [1998] recognized the high Ar abundance implied by the detection claim, and attributed it to a previously unsuspected, large scale height (i.e., coronal) Ar population in the lunar atmosphere. Given the importance of this issue to various aspects of lunar studies, one clearly desires a second measurement with better Signal-to-Noise ratio (S/N) to resolve the validity of the claimed detection.

As noted above, LACE also positively detected helium (during the lunar night), in the form of  $^4\text{He}$ , which has no counterpart in the suite of artifactual contaminants.<sup>[9]</sup> As shown in Figure 1.3, LACE observed nighttime helium maxima varying in the range of  $2\text{--}4 \times 10^4 \text{ cm}^{-3}$ . Based on this number density, the total  $^4\text{He}$  content of the lunar atmosphere, including  $^4\text{He}$  in satellite orbits, is  $\sim 10^{30}$  atoms, or  $7 \times 10^6$  g (7 tons). LACE observations demonstrated that the helium number density regularly rose and fell by a factor of 20 during the lunar diurnal cycle, approximately following the expected  $n \sim T^{-5/2}$  exospheric model for noncondensable species [Hodges and Johnson, 1968].<sup>[10]</sup> Superimposed on this diurnal cycle were He abundance fluctuations correlated with fluctuations in the geomagnetic index  $K_p$ , and hence the solar wind, such that the solar wind  $\alpha$ -particle flux  $\phi_\alpha$  required to generate the observed lunar helium follows  $\phi_\alpha = (5.6 \pm 1.9 + 0.44K_p) \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$  [Hodges, 1975]. The direct correlation of  $K_p$  with He abundance is discussed again in §3.2 and §3.3.

The absence of solar wind H, C, and N in the LACE and other data sets has been attributed to the reduction of these species on the surface to  $\text{H}_2$ ,  $\text{CH}_4$ , and  $\text{NH}_3$ , respectively [e.g., Hodges, 1975]. Hodges et al. [1973] used LACE data to set an upper limit of  $8 \times 10^4 \text{ cm}^{-3}$  on the maximum diurnal lunar  $\text{H}_2$  abundance; this nighttime constraint is consistent with the Apollo 17 ultraviolet spectrometer (UVS) daytime  $\text{H}_2$  upper limit of  $1.4 \times 10^3 \text{ cm}^{-3}$  [Hodges, 1973].

Finally with regard to LACE, I will discuss the reported detection of species with masses at 15–16 amu, 28 amu, and 44 amu [Hodges and Hoffman, 1975]. Signals at these mass channels were obtained in pre-sunrise data, indicating either O or  $\text{CH}_4$  for the 15–16 amu signal,  $\text{N}_2$  or CO for the 28 amu signal, and  $\text{CO}_2$  for the 44 amu signal.<sup>[11]</sup> In all three

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<sup>[9]</sup> Except possibly He outgassed from the Apollo Lunar Surface Experiment Package (ALSEP) nuclear power supply; however, the correlation of [He] with geomagnetic index argues that this contribution must be small. By contrast,  $^3\text{He}$ , like H and  $\text{H}_2$ , could not be detected in this instrument owing to internal backgrounds in mass channels 1, 2, and 3; [R.R. Hodges, pers. comm. 1997].

<sup>[10]</sup> The He density difference seen in Figure 1.3 from the  $n \sim T^{-5/2}$  law is due to incomplete thermal accommodation.

<sup>[11]</sup> O is considered unlikely because it should naturally oxidize, e.g., with reduced iron in the surface to FeO [Hodges, pers. comm. 1997]; also, the Apollo 17 UVS set a strict upper

cases, the signal increase began several hours before sunrise, and continued to rise until the instrument became background saturated around sunrise. Hodges [1975] analyzed these signals in terms of specific atmospheric species and derived model-dependent sunrise concentrations near  $1 \times 10^4 \text{ cm}^{-3}$ ,  $8 \times 10^2 \text{ cm}^{-3}$ ,  $1 \times 10^3 \text{ cm}^{-3}$ , and  $1 \times 10^3 \text{ cm}^{-3}$  for  $\text{CH}_4$ ,  $\text{N}_2$ ,  $\text{CO}$ , and  $\text{CO}_2$ , respectively. Unfortunately, the Apollo 17 UVS upper limits on these same species were not sufficiently sensitive to confirm these reports.

I now turn to *orbital* measurements of neutral species. The first clear orbital detections of native lunar gas were obtained from the Apollo 15 (July–August, 1971) and 16 (April, 1972) orbital Alpha Particle Spectrometer (APS) experiments [Gorenstein et al., 1973], which were designed to detect alpha particles from the noble gas  $^{222}\text{Rn}$ , and its daughter product  $^{210}\text{Po}$  (themselves decay products in the Ur and Th decay chains), as an indicator of either lunar internal outgassing or sites of high concentrations of radioactive decay products;<sup>[12]</sup> see Figure 1.4.

$^{222}\text{Rn}$  was detected at an average level near  $10^{-3}$  that of terrestrial concentrations. This emission was found to be concentrated over a small number of localized sites (“hot spots”) of scale  $\sim 150 \text{ km}$  in diameter, most notably the Aristarchus/Marius Hills region, Grimaldi, and possibly Alphonsus and Tsiolkovsky. Both the Aristarchus/Marius Hills region and Grimaldi have been frequently reported to be sites of lunar transient optical phenomena (see §1.2 above). Both of these regions were experiencing lunar night when Rn was detected over them. Bjorkholm et al. [1973] demonstrated that the Rn emission they detected could not have plausibly come from a surface enriched in radioactive decay products, because Apollo orbital gamma ray spectrometers would have found a correlated emission source in their data. Based on this, they concluded that the Rn must have originated from outgassing from localized source regions.

As noted above,  $^{210}\text{Po}$ , which is a daughter product of  $^{222}\text{Rn}$  decay, was also detected by the Apollo 15 and 16 Alpha Particle Spectrometers. The  $^{210}\text{Po}$  emission was found to be spatially correlated with mare/highland boundaries [Gorenstein et al., 1974]. Importantly, the polonium was detected in disequilibrium excess concentrations compared to  $^{222}\text{Rn}$ . The combination of Rn and Po in the radioactive disequilibrium ratio seen by the Apollo 15 and 16 alpha particle instruments provides evidence for both real-time (due to the  $^{222}\text{Rn}$ ’s 3.8 d half-life) and more long-term lunar release (due to the Pb precursor of  $^{210}\text{Po}$ ’s 21 year half-life).

The Lunar Prospector mission carried an alpha particle spectrometer much like the Apollo 15 and 16 instruments into orbit for a 1-year mission that began in early, 1998. The

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limit of  $500 \text{ cm}^{-3}$  on O, at odds with the LACE “detection” at 16 amu.

<sup>[12]</sup> Turkevitch et al., [1970] reported some previous but less secure evidence for Rn emission in Surveyor lander alpha particle spectrometer data.

flight of this instrument should vastly enhance knowledge of Rn, Po, and other radioactive daughter products in the lunar atmosphere. However, as of this writing in early 1999, no scientific results from this instrument have been released.

The Apollo 15 and 16 spacecraft also carried mass spectrometers into lunar orbit, which should have been capable of measuring the global distribution of many species. However, these instruments were heavily contaminated by effluents from the Apollo Command/Service Modules on which they flew. As a result, no detections or useful upper limits were therefore obtained from these instruments [Hodges et al., 1972; Hodges, pers. comm. 1991].

Finally, on Apollo 17 late in 1972, a high-throughput UV spectrometer with a 1180–1680 Å bandpass was operated in lunar orbit for 6 days aboard Apollo 17. Although searches for resonance fluorescence lines of H, O, C, N, Kr, Xe, H<sub>2</sub>, and CO were made, no detections were obtained [Fastie et al., 1973]. Feldman and Morrison [1991] reanalyzed the Apollo 17 UVS data set and although they also made no detections, they used improved resonance fluorescence g-factors to obtain revised upper limits on all of these species, as well as atomic S; these and other results are summarized in Table 1.1.

In addition to direct observations, an additional set of orbitally atmospheric constraints were derived during the Apollo era by Siscoe and Mukherjee [1972] and Mukherjee [1975], who exploited the absence of evidence in Explorer 35 data for solar wind mass loading by the lunar atmosphere. Their results, which assume a T=300 daytime exosphere, provide upper limits on H, H<sub>2</sub>, He, Ne, O<sub>2</sub>, N<sub>2</sub>, NO, CO, CO<sub>2</sub>, N<sub>2</sub>O, and CH<sub>4</sub> in the range 10<sup>3</sup>–10<sup>4</sup> cm<sup>-3</sup>. The Explorer 35 and Apollo 17 results continue to provide the best available constraints into what molecular species may reside in abundance in the *daytime* lunar atmosphere.

## 1.5 Suspended Dust in the Lunar Atmosphere

Although largely beyond the scope of this review, it is worthwhile to briefly discuss the evidence for suspended dust above the lunar surface, and hence “in the lunar atmosphere.”

The discovery of this dust was made in post-sunset Surveyor lunar lander TV camera images of the lunar horizon (e.g., Norton et al., [1967]; Shoemaker et al., [1968]). Surprisingly, these Surveyor images revealed the presence of a near-surface (e.g., scale height ~10–30 cm) glow that was observed to persist for several hours after sunset, and to have a brightness near 10<sup>-6</sup>B<sub>⊙</sub>. Rennilson and Criswell [1974] eliminated the possibility that this signature was caused by gas, based on scale height and density constraints, and instead interpreted the cause of the forward-scattered light as a population of 5–10 μm grains with a column density of ~50 μg cm<sup>-2</sup>.

Additional information relating to the source of this phenomenon was obtained by the Apollo 17 Lunar Ejecta and Micrometeoroids (LEAM) surface experiment (e.g., Berg et al., [1976]), which operated for several years. For several hundred hours around lunar sunrise (indeed, beginning as much as 150 hours prior), signals from LEAM were found to be dominated by a population of low-energy impacts. A smaller and shorter-lived pulse of signals was also seen at each sunset. The LEAM signatures were attributed to either electrostatically levitated [Gold, 1955; McCoy, 1976], or possibly photoemission-levitated, submicron dust particles in transport across the terminator by the large (e.g., 0.2–1 V cm<sup>-1</sup>) electric potentials generated there by the highly resistive nature of the surface (see Berg et al., [1976, 1978]; Criswell [1973]; Zook et al., [1994, 1995]).

Optical evidence for even higher-altitude lunar dust was later obtained from horizon glow studies by (i) the Lunokhod 2 dual-channel (2700 Å, 5400 Å) photometer (e.g., Severnyi et al., [1975]), (ii) the Apollo 16 surface far-UV spectrographic camera [Carruthers and Page, 1972], (iii) Apollo 15 and 17 orbital photography, (iv) Apollo crew visual sightings of lunar sunrise “streamers” [McCoy and Criswell, 1974; see Figure 1.5], and (v) Clementine imagery [Zook et al., 1994, 1995]. The brightness of these glow signatures, which has been estimated to have a scale height of 10s of km, vary between 10<sup>-13</sup>B<sub>⊙</sub> and 4×10<sup>-12</sup>B<sub>⊙</sub> (in Zook et al.’s units). Zook et al. [1995] have also shown there is the possibility that the Apollo visual observations and orbital photography of Lunar Horizon Glows (LHGs) with scale heights of 10s of km could have involved visual detection of the then-unknown 3–10 kR-class Na/K emissions. Zook et al. [1995], like others, point out that the brightness of this glow is ~10<sup>5</sup> times too great to be explained by micrometeoroid-generated ejecta from the lunar surface, and opts for an electrostatic source.

## 1.6 Groundbased Discoveries and the Study of Na and K

The close of the Apollo flight program in 1972 and the termination of ALSEP data collection in 1977 created a hiatus in observations of the lunar atmosphere that lasted about a decade. This hiatus was caused primarily by the fact that at the time the Apollo data collection ended, none of the then-known lunar atmospheric species could be detected by groundbased or spacebased optical remote sensing techniques.

However, a major breakthrough was achieved in 1988 with the 1987 discovery of D<sub>2</sub>-line emission from atomic K and then Na in the lunar exosphere [Potter and Morgan, 1988a]. An independent discovery of lunar Na was also made by Tyler, Kozłowski, and Hunten, [1988]. The detection of these species was achieved via long-slit, high-resolution (R>50,000) spectroscopy, motivated by the 1985–1986 discoveries of Na and K in Mercury’s exosphere by the same groups (see Hunten et al., [1988] for a review). The high spectral resolution used in these detection observations was needed to provide suitable contrast between the weak lunar Na signal and instrument-scattered light from the far stronger

surface reflection.

Potter and Morgan [1988a] found subsolar limb brightnesses of  $3.8 \pm 0.4$  kilorayleighs (kR) for Na and  $1.8 \pm 0.4$  kR for K; these brightnesses correspond to estimated zenith column densities at the subsolar point of  $N_{\text{Na}} = 8 \pm 3 \times 10^8 \text{ cm}^{-2}$  and  $N_{\text{K}} = 1.4 \pm 0.3 \times 10^8 \text{ cm}^{-2}$ . Measured scale heights of  $H_{\text{Na}} = 120 \pm 42 \text{ km}$  and  $H_{\text{Na}} = 90 \pm 20 \text{ km}$  in their data set indicated that the observed Na was approximately in thermal equilibrium with the surface, and were used to derive estimated surface number densities of  $n_{\text{Na}} = 67 \pm 12 \text{ cm}^{-3}$  and  $n_{\text{K}} = 15 \pm 3 \text{ cm}^{-3}$ . Figure 1.6 shows some of the earliest published Potter and Morgan Na data. The  $6 \pm 3$  Na/K abundance ratio obtained from these data is close to the Na/K abundance ratio in lunar soils [Williams and Jadwick, 1980; Taylor, 1982]. The independent discovery of lunar Na by Tyler et al. [1988] found quantitatively similar brightnesses, scale heights, and abundances.

Given the fact that the combined number density of Na and K in the lunar atmosphere is only  $\sim 10^2 \text{ cm}^{-3}$ , these constituents are clearly only minor species in the lunar atmosphere. However, the detectability of Na and K from Earth makes them highly valuable probes of the lunar atmosphere. As such, many dozens of spectroscopic and imaging observations of these species have been reported, yielding a treasure trove of information on the dynamics and source processes of these alkali species. The most important results of the Na and K observations may be briefly summarized as follows.

I begin with the spectroscopic results. Potter and Morgan [1988, 1991] detected Na at altitudes as great as 1500 km ( $0.9 R_M$ ), indicating the presence of a second, nonthermal population of sodium atoms in the lunar atmosphere with  $H \approx 600 \text{ km}$  (see Morgan and Shemansky [1991], and Figure 1.7 here). Similarly, Kozłowski et al. [1990] measured K abundances up to, 190 km above the surface, and found the K vertical profile to also be best fit by a two-temperature component atmosphere [ $H_1 = 52 \text{ km}$ ,  $T_1 = 395 \text{ K}$ ,  $H_2 = 329 \text{ km}$ ,  $T_2 = 2500 \text{ K}$ ]. Sprague et al. [1992] confirmed the high-altitude Na with observations up to 610 km. Both Potter and Morgan [1991] and Sprague et al. [1992] reported evidence for a systematic increase in Na scale height with lunar latitude, indicating a change in source process with solar zenith angle. Hunten et al. [1991] then reported that observations made on 12, 13, and 14 October 1990 revealed a 60% growth over this period of the Na signal above the lunar south pole, despite the fact that the Na signal above the equator on the same three dates remained constant within their detection limits. Potter and Morgan [1994] reported a systematic decrease in Na column abundance away from full Moon, but did not make clear how much of this is simply due to geometrical circumstances (i.e., line of sight effects). Both Mendillo et al. [1993] and then Potter and Morgan [1997] reported empirical evidence showing that the Na abundance decreases with solar zenith angle,  $\chi$ . These findings (see Figure 1.8) indicate that because strictly flux-dependent sources should decline only like  $\cos(\chi)$ , the source responsible for the steep Na falloff must have some

additional, solar zenith angle dependence on flux, temperature, or another parameter. Potter and Morgan suggested that chemical sputtering may be the culprit, since the falloff depends both on incident flux like  $\cos(\chi)$ , and also exponentially on temperature for the release rate. Further interpretations of these findings will be discussed in §2 and §3.

Let's now turn to imaging studies. Beginning with the pioneering work of Mendillo and coworkers [Mendillo et al., 1991], two-dimensional, direct imaging of the lunar Na has also been undertaken. Mendillo's team uses a Lyot-stop coronagraph with a 6 deg field of view (FOV) and a narrow-band Na D-line interference filter to image Na at altitudes  $>1.5R_M$ . In their initial report, Mendillo et al. [1991] described the detection of Na emission out to  $4 R_M$  (almost 7,000 km) on the dayside, and to 15–20  $R_M$  on the nightside. They also found that the radial dependence of brightness and hence column density (given the optically thin nature of the emissions) above the subsolar region is well fit by an  $R^{-4}$  power law. These data dramatically confirmed the reality of the nonthermal Na atom population that had been discovered spectroscopically. Flynn and Mendillo [1993] extended this work with whole-Moon Na images; Figure 1.9 shows such an image.

Mendillo et al.'s images, like previous spectroscopic work (see Sprague et al., [1992]), revealed that the Na distribution becomes progressively fainter and more extended toward the poles. Flynn and Mendillo [1993] found that the Na brightness profile can be fit to an  $I(R,\chi)=I_0(\chi)R^\alpha(\chi)$  dependence, where  $\chi$  is the solar zenith angle. For the quarter-Moon geometry they observed, they found  $I_0=(1+6\cos^8\chi)$  kR and  $\alpha(\chi)=-2(1+\cos^2\chi)$ .

More recently, Mendillo's team obtained images of the high-altitude Na exosphere during the 29 November 1993 [Mendillo and Baumgardner 1995] and 4 April 1996 [Mendillo et al., 1997a] lunar eclipses, revealing emission out to  $10 R_M$  (at  $10 R_M$ , 32 R of background-subtracted lunar emission was found). For the 1993 eclipse, the full-Moon geometry revealed an  $R^{-8}$  power law brightness distribution, with no significant azimuthal asymmetry. For the 1996 eclipse, azimuthal symmetry was again observed, but a different radial structure was seen: Inside  $4 R_M$  the brightness declined like  $R^{-3}$ , indicating a bound population of Na atoms; outside  $4 R_M$  the brightness declined like  $R^{-1}$  (much like a comet's freely escaping, spherically symmetric coma). For the 1993 eclipse case, the Na intensity profile  $I(R,\chi)$  fit was determined to have  $I_0\approx 1$  kR and  $\alpha=-2$ , independent of  $\chi$ . Taking into account the differing observation geometry and the fact that the eclipse observations primarily sampled the terminator atmosphere ( $\chi=90$  deg), these observations are seen to be consistent with the  $I(R,\chi)$  fit Flynn and Mendillo [1993] found from atmospheric imaging at quarter-Moon, and as modelled under both full- and quarter- Moon conditions by Mendillo et al., [1997b].

Meanwhile, Stern [1992] developed an independent imaging technique based around Na observations over the dark side of the lunar terminator, where surface illumination is lim-

ited to reflected Earthlight and the atmospheric Na can thus be detected directly against the disk. This technique complements the high-altitude coronagraphic imaging of Mendillo and coworkers by being able to obtain images quite close to the terminator, allowing Na profiles to be extended down to 50 km ( $0.03 R_M$ ) altitude.<sup>[13]</sup> Stern and Flynn [1995] reported an analysis of Na images made this way over a variety of latitudes in the northern lunar hemisphere. Applying a simple Maxwellian exosphere model, these workers confirmed that both hot and cold Na populations are required to adequately fit the radial intensity behavior. They also discovered that the mixing ratios and temperatures of the two components vary systematically with latitude such that the ratio of hot, coronal gas to warm thermal gas progressively increases as one moves toward the pole. Figure 1.10 illustrates some of these results.

### 1.7 Groundbased Observations Yielding Upper Limits on Other Neutral Species

Because the Apollo total pressure measurements indicate surface number densities far in excess of the total number density of identified species, it seems that much of the lunar atmosphere remains compositionally unidentified. This conclusion has led to observations in search of the “missing species,” as I now describe.

Flynn and Stern [1996] began this work with an extensive search for additional neutral species in the lunar atmosphere. Their search was based on the naive, but reasonable first assumption of a simple stoichiometric exosphere that reflects the surface elemental composition, adjusted for species loss times (with species brightnesses further adjusted for scale height and resonance fluorescence efficiency [g-factor] effects). Such an assumption was bolstered by the fact that the Na/K ratio in the lunar atmosphere is the stoichiometric relative to the lunar surface. The stoichiometric model Stern and Flynn constructed predicts that relatively abundant lunar *surface* constituents such as Si, Al, Ca, Mg, Fe, and Ti should be more abundant in the lunar atmosphere than is either Na or K.

Flynn and Stern [1996] investigated this hypothesis by searching for solar resonant scattering lines of nine metallic neutrals between 3700 and 9700 Å using the 2.7 m coudé and the 2.1 m Cassegrain Echelle spectrographs at McDonald Observatory. Spectra were taken 20 arcsec above the subsolar limb of the Moon near quarter phase on 30 July 1994 and 10–12 March 1995. Upper limits were obtained for the first time for the abundant lunar surface species Si, Al, Ca, Fe, Ti, Ba, and the alkali Li. Their results are summarized in Table 1.1 and Figure 1.11. In the cases of Si, Ca, Fe, and Ti, the derived upper limits were more than an order of magnitude lower than their stoichiometric model predictions.<sup>[14]</sup> These

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<sup>[13]</sup> Potter and Morgan’s [1998] success in obtaining near-surface Na images using a coronagraphic technique with narrow-band interference filters opens a new channel for additional imaging observations.

<sup>[14]</sup> The derived upper limits for Li and Al are less constraining.

workers concluded that the stoichiometric Na:K ratio is peculiar in that the mechanism(s) that produce the lunar Na and K atmosphere somehow favor those atomic species over many other abundant lunar surface species.

Flynn and Stern [1996] noted that the lack of stoichiometry may indicate that the very lunar surface (i.e., the layer in contact with the atmosphere) may not have reached radiation exposure equilibrium. This could occur, for example, if meteoritic bombardment sufficiently gardens the lunar surface to result in a reduced effective surface age [Johnson and Baragiola 1991]. In this case, solar wind sputtering yields would not approach stoichiometry and volatile species would dominate atmospheric metal abundances.

The lack of additional species detections continued, despite attempts to apply other techniques. The first of these was a set of imaging spectrograph observations made at large distances from the Moon during the 4 April 1996 lunar eclipse [Mendillo et al., 1997a] which detected no emission other than Na in a wide, 5800–7700 Å bandpass.

Next, Stern et al., [1997] reported using the Hubble Space Telescope’s (HST’s) Faint Object Spectrograph to make a mid-UV spectroscopic search for emissions from the lunar atmosphere. This spectrum revealed no emission lines, despite the fact that strong resonance emission transitions from the Al, Si, and Mg neutrals, and  $\text{Mg}^+$ , are present in the bandpass. The most constraining upper limit they obtained was for Mg, which was found to be depleted by a factor of at least nine relative to model predictions which use the known abundance of Mg in the lunar regolith. The  $5\sigma$  upper limits derived on the atmospheric abundances of each of these species, and OH (0-0), emission are also presented in Table 1.1. These findings reinforce the conclusions of the groundbased search for neutral atoms in the lunar atmosphere: the missing species remain missing, and stoichiometry does not obtain.<sup>[15]</sup>

As I describe further in §3, Sprague et al. [1992] argue for Na and K’s ability to efficiently recycle as the reason for their high abundance relative to other species. Alternatively, Na and K may be unique in their ability to sputter from refractory surfaces as atomic neutrals. Thus, the lack of other abundant surface species in the atmosphere may indicate that either thermal desorption or chemical sputtering (see Potter and Morgan [1978], both of which favor high-vapor pressure species like Na and K, is occurring; or it may indicate that the other metal species may be preferentially injected as molecular fragments (e.g., CaO, TiO,  $\text{TiO}_2$ , etc.) rather than atoms. However, searches for CN in the optical and CO, HCN, and SiO using millimeter-wave telescopes by this author and coworkers M. Mendillo, J. Wilson, and M. Womack have as yet yielded only negative results.

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<sup>[15]</sup> Interestingly, searches for Ca [Sprague et al., 1993] and Li [Sprague et al., 1995] in Mercury’s exosphere, and for a broad array of neutrals in Io’s Na/K exosphere [Na et al., 1998], have also yielded negative results (see §4 for additional details).



## 1.8 Lunar Water

Let us now turn to the subject of lunar water. Although there has never been a confirmed detection of water or its dissociation products, H and OH, in the lunar atmosphere, the possibility of cold-trapped deposits of H<sub>2</sub>O ice has been a subject of scientific speculation for almost four decades. One reason for this long-standing interest is the obvious potential of H<sub>2</sub>O as a resource available for human exploration of the Moon. I suggest that a more scientific motivation is the potential for study of the isotopic (i.e., D/H and <sup>16</sup>O/<sup>17</sup>O/<sup>18</sup>O) abundances in the ice, which is presumably cometary in origin.

There is little question that a source of exogenous lunar water exists via deposition from the meteoritic complex and occasional cometary impacts. Morgan and Shemansky [1991] have estimated that the *meteoritic* H<sub>2</sub>O source rate is of order 0.5–5 g s<sup>-1</sup>. The *cometary* source, though highly sporadic, is thought to provide a time-averaged source rate of order 75 g s<sup>-1</sup>. The surface reduction of oxygen-bearing minerals via solar wind bombardment [Thomas, 1974] may provide another, though smaller, source.

Thus, although the fact that a source of water to the Moon exists is incontrovertible (and therefore has deposited  $\sim 10^{17-19}$  g onto the Moon over the last 4 Gyr), impacting water molecules must survive impact (avoiding both ionization and impact jetting) to be retained even briefly in the lunar environment. The molecules are then subject to photon-driven destruction as they transport across the Moon in a diffusive “search” for safe havens.

The key question then is how much of the H<sub>2</sub>O which impacts the Moon actually survives to reach a cold-trap reservoir. Arnold [1979] has estimated that the chondritic meteor flux is  $\sim 2\%$  water by mass. Morgan and Shemansky [1991] estimate the sticking fraction of water impacting in the meteoritic complex to be of order 25%. To avoid subsequent, and indeed rapid loss (the timescale for water destruction by UV sunlight at 1 AU is  $\sim 1$  day), the water molecules must find safe haven by random walking their way around the surface of the Moon’s “griddle hot” surface until they find a cold-trap.<sup>[16]</sup> The efficiency of this diffusive transport is not well established, but even if it is just 1%, then  $10^{16-17}$  g of water should have migrated to the lunar poles over time, corresponding to some 100–1000 g cm<sup>-2</sup> of water embedded in the traps (if no loss processes existed there to remove it).

Watson et al. [1961], Arnold [1979], Lanzerotti et al. [1981], Hodges [1991], and Morgan and Shemansky [1991] have each examined the possibility of stable cold-traps (25 K < T < 95

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<sup>[16]</sup> As to observationally based constraints, Morgan and Shemansky predict a typical subsolar limb brightness of 50 R of OH resulting from H<sub>2</sub>O loss to photodissociation (the dominant loss mechanism). The best existing observational constraint on OH, a  $5\sigma$  upper limit of 67 R, obtained by HST [Stern et al., 1997], is hardly constraining.

K) in the permanently shadowed floors of deep craters at the poles. It has been found that although such traps would indeed be thermally stable over billions of years, both charged particle sputtering and Ly $\alpha$ -driven photodissociation (the Ly $\alpha$  being solar, and reaching the shadowed areas by scattering off H in the interplanetary medium) would still act as loss processes, etching away exposed deposits at the rate of  $\sim 7 \times 10^{-8}$  mm yr $^{-1}$ . Hence, to achieve true stability, the water ice in polar deposits must be buried (in a chemically nonreactive regolith), and the question becomes whether the lunar burial rate ( $\sim 2$  m/Gyr; Arnold [1979]) is rapid enough to shelter it more rapidly than it is lost.

The issue of the viability of lunar polar ice deposits has long been data starved, but that situation is now changing. This change began when Nozette et al. [1996] reported evidence for an ice like scatterer of radio waves at the lunar south pole, detected through a bistatic radar experiment using the Clementine lunar orbiter. Although Nozette et al.'s report received much attention, it has been called into question by Goldstone radar results reported by Stacey et al. [1997]. At the root of this controversy are the facts that radar sounding of the lunar pole is difficult, and radar signatures (unlike spectra) do not succumb to a unique chemical interpretation.

The 1998–1999 Discovery Lunar Prospector (LP) mission [Binder, 1998] had a major objective of searching for evidence of polar ice using a gamma ray/neutron spectrometer capable of directly detecting neutron emission from hydrogenated deposits down to depths of order 0.3–3 m, depending on the local surface dielectric constant and compaction state. And indeed, LP's neutron spectrometer team reported that H concentrations in the surface layer reach maxima at each pole [Feldman et al., 1998]. This result was interpreted by the LP team as evidence of exposed or lightly buried H<sub>2</sub>O ice deposits in these regions. Assuming a total of 1850 km<sup>2</sup> of permanently shadowed terrain in the north and south poles, and that all of the H excess they detected derives from H<sub>2</sub>O ice, Feldman et al. concluded that each polar region must contain  $\sim 3 \times 10^{15}$  g of H<sub>2</sub>O in the uppermost 2 m of the regolith. Although the neutron spectrometer's H<sub>2</sub>O ice interpretation is both indirect and based on several key assumptions, the Lunar Prospector results have clearly shifted the debate in favor of there being polar water ice deposits. What one clearly desires next is the actual detection of chemical signatures of water ice, either by orbiting or *in situ* instruments.

## 1.9 AMPTE and WIND Detections of Lunar Ions in the Solar Wind

As I have described, the highly nonthermal populations of Na and K provide strong evidence for a nonthermal source mechanism, such as meteoroid impact or sputtering. This in turn naturally suggests the possibility that many other elements in the surface (the “very regolith”) could also be present in the atmosphere. Elphic et al. [1991] studied these production processes in the laboratory, using a simulated, keV-class He<sup>++</sup>, Ar<sup>+</sup> solar wind ion beam on lunar soil samples and sample simulants, and found a rich variety of sputter

products, dominated by neutrals but containing a few percent ions by number.

About the same time that Elphic et al.'s work was published, Hilchenbach et al. [1991] announced the finding that their time-of-flight ion mass spectrometer [SULEICA] aboard the high-Earth-orbit AMPTE (Active Magnetospheric Particle Tracer Experiment) spacecraft had detected singly ionized solar wind pick up ions of lunar origin during observations made in August-September 1985. As shown in Figure 1.12, the ion mass distribution detected by the AMPTE/SULEICA instrument (m/q resolution  $\sim 10\%$ ), when it was down solar wind of the Moon, was dominated by peaks consistent with  $O^+$  (16 amu) and either Al (26 amu), Si (28 amu), or perhaps S (34 amu).<sup>[17]</sup> Although many heavy species would not have been detectable within AMPTE/SULEICA's e/q bandwidth, Hilchenbach et al. [1991] reported that the instrument's upper range channel sensitive to singly ionized species with 40–60 amu, obtained evidence consistent with the marginal detection of  $Ar^+$ ,  $Ca^+$ , and  $Fe^+$ . Hilchenbach et al. [1993] estimated that the  $0.3 \text{ ions cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ keV}^{-1}$  flux they detected in the 23–37 amu “Al/Si” band corresponds to a source characteristic production rate of  $\sim 3\text{--}31 \text{ ions cm}^{-2}$  at the Moon.

Shortly thereafter, Cladis et al. [1994] reported a detection (at  $8\sigma$  confidence) of singly ionized lunar pickup ions in the 23–40 amu range, using ISEE-1 spacecraft data, and described a set of transport calculations that verified the ability of lunar ions, created by an ion source like that observed in Elphic et al.'s laboratory experiments, to reach spacecraft in high Earth orbit with angular distribution and energy characteristics like those observed with AMPTE and ISEE-1.

Despite the fact that the transport of ions from the Moon to a spacecraft in high Earth orbit is dependent on many poorly known variables, the observational evidence supporting a *lunar* origin for these ions is strong: The ions were detected in a relatively narrow cone ( $\sim 30$  deg width) when the spacecraft was near apogee ( $18.7R_{Earth}$ ), in the solar wind upwind of the Moon but outside the Earth's magnetospheric bowshock [Hilchenbach et al., 1991, 1993], such as one would expect from surface or atmospheric sputter products accelerated by the near-surface dayside lunar electric potential.

Recently, the STICS ion spectrometer aboard the WIND spacecraft has also reported detections of lunar pickup ions, attributed to  $O^+$  and  $Al^+$ ,  $Si^+$ , or possibly  $P^+$  [Mall et al., 1998].

## 2.0 STRUCTURE AND DYNAMICS OF THE LUNAR ATMOSPHERE

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<sup>[17]</sup> Johnson and Sittler [1990] and Elphic et al. [1991] report that typical sputter products have excess energies of 5–10 eV; the escape energy for Si and Al ions from the lunar potential well is  $\approx 1$  eV.

It is easily demonstrated that the total number density at the base of the lunar atmosphere is so low that any atom or molecule traveling upward from the surface with  $v > v_{\text{escape}}$  ( $2.38 \text{ km s}^{-1}$ ) is unlikely to suffer a collision with another gas atom or molecule.<sup>[18]</sup> Put another way, the mean free path in the lunar atmosphere greatly exceeds the atmospheric scale height; as such, the atmosphere is an exosphere in which collisions play a very minor role,<sup>[19]</sup> and structure and dynamics are controlled almost entirely by ballistic kinematics.

Owing to the fact that individual atoms and molecules do not commonly communicate via collisions, each gas species can be thought of as forming a *separate* lunar atmosphere with its own distinct structural and dynamical properties. Owing to this approximation, the literature is laced with the terminology of the “lunar atmospheres.” The structure and dynamics of each of these species-segregated lunar atmospheres is controlled by the source rates and energetics, loss rates, gas-surface interaction physics, and transport susceptibility unique to that species.

In what follows here in §2, I review the essential details of the structure and dynamics of the neutral lunar atmospheres, dividing them into two groups: the noble gas atmospheres discovered in the Apollo era, and the alkali atmospheres discovered and subsequently studied by groundbased techniques. First, however, I briefly describe some dynamics of the lunar ionosphere.

## 2.1 The Lunar Ionosphere: Some General Considerations

An important subtopic, largely beyond the scope of this review, is the dynamics of ions, which for the most part are formed as a result of neutral loss processes. Lunar ion dynamics are controlled by the force felt from the local electric field. This electric ( $\mathbf{E}$ ) field is usually dominated by the solar wind  $\mathbf{E}$  field, except during magnetospheric passage each month, when it is dominated for a few days by the  $\mathbf{E}$  field of the terrestrial magnetotail. The  $\mathbf{E}$  field direction (except very near the lunar surface) is essentially perpendicular to both the

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<sup>[18]</sup> The lunar escape velocity corresponds to energy and gas temperature requirements of  $0.03 \text{ eV/amu}$  and  $226 \text{ K/amu}$ , respectively.

<sup>[19]</sup> It is often not appreciated that the lunar atmosphere is not strictly a perfect, collisionless exosphere. In fact, the mean free path against gas-gas collisions is of order  $10^{11} \text{ cm}$ ; for the gravitationally bound, thermal component of the lunar atmosphere the average distance traveled before loss to photoionization is sufficiently large (e.g., at  $400 \text{ K}$ :  $\sim 4 \times 10^{10} \text{ cm}$  for Ar,  $\sim 2 \times 10^9 \text{ cm}$  for Na,  $\sim 1 \times 10^9 \text{ cm}$  for K) that a finite, nontrivial collision probability exists for each species. Crude scaling calculations reveal that Na and K atoms have an  $\sim 1\%$  probability of collision with another gas species prior to photoionization, and that an Ar atom has a probability of several tens of percent of suffering such a collision. Clearly, weak but nonzero gas-gas thermal and even chemical communication pathways do exist in the lunar atmosphere.

solar wind<sup>[20]</sup> velocity and the magnetic ( $\mathbf{B}$ ) field. The scale lengths over which the  $\mathbf{E}$  and  $\mathbf{B}$  fields of the solar wind are comparatively uniform are of order 0.01 AU, roughly  $10^3$  times the radius of the Moon. Ions are accelerated either away from the Moon or toward it depending on the direction of the local  $\mathbf{E}$  field, with on average about half of the ions being driven back to the lunar surface, where they are often implanted at high energies [Manka and Michel, 1971]. For ions traveling upward, escape to infinity is the result. For all but the lightest ions, the gyro radius is much greater than the lunar radius, and escape occurs within one gyro period. Readers interested in this topic are referred to a more complete discussion by Vondrak [1988].

## 2.2 The Neutral Helium and Argon Exospheres

Knowledge of the structure and dynamics of the helium and argon exospheres of the Moon is limited by the lack of detailed information on the energetics, and therefore the thermal distribution, of the lunar He and Ar gas. This ignorance is partially compensated for by the fact that He and Ar are noble gases, which greatly simplifies their surface chemical interaction. As a result, studies of the structure and dynamics of lunar He and Ar have assumed a purely thermal source population initially derived from surface desorption.

The assumption that the velocity distribution functions of He and Ar are purely thermal produces an equilibrium exosphere with scale heights  $H_{He} \sim 1000$  km and  $H_{Ar} \sim 50$  km, assuming a gas temperature of 400 K typical of atoms thermally accommodated to the daytime lunar surface. Radiation pressure and solar/terrestrial gravity affect the trajectories of He and Ar atoms, as shown by Hodges [1973, 1978]. Here, however, I restrict this discussion to the near surface (e.g., bottommost scale height) of the lunar He and Ar exospheres.

In the late, 1960s, even before any evidence of a the lunar atmosphere was discovered, Hodges and Johnson [1968] demonstrated that in hydrostatic equilibrium, one would expect lateral flow in the lunar exosphere to establish a number density ( $n$ ) distribution controlled by the relation  $nT^{5/2} = \text{constant}$ .

More specifically, Hodges et al. [1973] has shown that the diffusion approximation of exospheric transport gives a source flux function  $\phi$  for noncondensable gases like He (condensation temperature 5 K) of the form:

$$\phi = \left( \frac{\alpha}{1 - \alpha} \right) \left( \frac{n\bar{v}}{4} \right) + \left( \Omega \frac{d(nH)}{d\theta} \right) - \nabla_h^2 n\bar{v}H^2, \quad (2.1)$$

where  $\alpha$  is the temperature-dependent sticking coefficient,  $\bar{v}$  is the mean velocity of the gas molecules,  $\Omega$  is the angular rate of rotation of the Moon,  $\theta$  is the subsolar longitude, and

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<sup>[20]</sup> Or the magnetotail, when the Moon is within it.

$\nabla_h^2$  is the horizontal component of the Laplacian operator in a Sun-referenced coordinate frame.

The discoveries of helium and argon in the early, 1970s allowed this result to be tested. And in point of fact, helium number densities were observed to follow prediction, producing a smooth and repeatable nighttime maximum in number density that was about 20 times that seen during the lunar daytime (the  $nT^{5/2}=\text{constant}$  relation predicts a 26:1 increase).<sup>[21]</sup> Figure 1.3 nicely illustrates this behavior with ALSEP LACE data.

In contrast, argon adsorption becomes important at 120 K, allowing it to accumulate on the nightside lunar surface. Consequently, whereas He gas should strictly follow the  $nT^{5/2}=\text{constant}$  relation, the condensation sink for Ar will break this relation, causing it to display a distribution which peaks at the terminator, has a minimum on the nightside, and a secondary minimum near the subsolar point.

### 2.3 The Neutral Sodium and Potassium Exospheres

As described in §1 above, the structure and dynamics of the lunar Na and K exospheres profited enormously from the rich data set of Na and K vertical profiles and Na images accumulated over the past decade. Among the most important findings was the fact that both Na and K atoms exhibit at least two distinct energy distributions: a “barometric” or “thermalized” (i.e., surface-accommodated) component, and a nonthermal (i.e., surface-unaccommodated) “coronal” component. These two energy distributions display qualitatively different styles of transport and degrees of surface interaction during their generation at sources and their loss to sinks. Figure 2.1 illustrates these two styles of dynamics, and also provides a kind of schematic overview of many of the sources and sinks at work in the lunar atmosphere.

Once liberated, energetic Na and K neutrals are subject to two primary forces: gravity and radiation pressure. The gravitational force is dominated by the Moon’s field, but is significantly influenced (particularly at high altitudes) by solar and terrestrial perturbation terms. Radiation pressure, which is effective only for atoms in sunlight, is of course dominated by the solar term, but a term due to lunar albedo pressure also plays a small role.

Consider first the cooler, thermal population. I begin with a heuristic discussion, and then proceed onward to a discussion of published model results. Owing to the much shorter flight times of the cooler, barometric Na and K populations, they are subject to both smaller radiation force effects, and weaker solar/terrestrial gravitational perturbations, than are

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<sup>[21]</sup> In contrast to number density  $n$ , I point out that the total He column,  $N_{He}=n_{He}H_{He}$ , behaves differently; because  $H\propto T$  but  $n\propto T^{-5/2}$ ,  $N\propto T^{-3/2}$  and  $N_{night}:N_{day}\sim 7:1$ .

the nonthermal Na and K populations. In effect, the barometric Na and K populations simply “hop” around the lunar dayside surface until they are either lost to ionization or find a temporary nightside refuge (i.e., until the Sun once again rises). As described by Hunten et al. [1988], at 400 K on the lunar dayside, the characteristic residence time for an adsorbed Na or K atom is  $<1 \mu\text{s}$ ; near the terminator or in a shadow, a 100 K surface will produce a characteristic residence time on the surface of order 1 second; on the lunar nightside, temperatures below  $\sim 60$  K will produce residence times in excess of  $10^6$  seconds, the timescale of a lunar night. During each residence on the surface, Na and K atoms can interact with the surface chemically and thermally. The efficiency of these processes is controlled by the local surface temperature, composition, and to a lesser extent, the local physical microstructure.

At  $T=400$  K, a typical hop for Na and K atoms reaches an altitude near 130 km and 75 km, respectively, and displays a typical lateral range near 90 km for Na and 55 km for K. Taking a diffusion (i.e., random walk) approach, one easily finds that the characteristic transport time ( $R_M/v_{therm}$ ) for an atom ballistically hopping over the lunar surface at  $T=400$  K is  $\approx 90$  hours for Na and  $\approx 200$  hours for K. These values can be compared to their photoionization loss timescales of 15 and 10 hours, respectively. Such considerations imply that ballistically hopping Na and K atoms in the barometric population rarely transport over length scales comparable to the lunar radius. As a result, one expects that the barometric Na and K populations, which are derived from the surface (see §3), should show mare/highland compositional gradients reflecting the Na and K abundance ratios between the mare and highland surface units. Owing to smoothing effects, this should be most evident in comparing lunar frontside and backside Na/K ratios, when that becomes possible.

As noted above, radiation pressure plays a more significant role in the dynamics of the nonthermal, coronal Na and K populations. The radiation pressure acceleration a given atom feels depends on its resonance scattering cross section (i.e., the details of its quantum mechanical interaction with the ambient radiation field). Importantly, this interaction cross section depends on the atom’s heliocentric radial velocity. Why? Because an atom traveling at a speed significantly different from rest will see the solar spectrum appropriately redshifted or blueshifted and will therefore experience flux at its photon resonant (i.e., Fraunhofer) frequencies that is increased over what it would see at rest, where the flux is limited to the level at the core of the solar Fraunhofer lines.

At zero velocity relative to the solar frame, sodium and potassium atoms feel accelerations of  $2.7 \text{ cm s}^{-2}$  and  $3.1 \text{ cm s}^{-2}$ , respectively. Variability up to  $\sim 50\%$  over the course of a year around these nominal values is caused by (i) seasonal effects due to the Earth’s motion about the Sun,<sup>[22]</sup> (ii) orbital effects due to the Moon’s motion around the Earth

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<sup>[22]</sup> This induces an  $\approx 2\%$  effect due to radiation field dilution as the Earth moves between

(1 km s<sup>-1</sup> amplitude, period 29.5 days), (iii) source velocity effects (e.g., ion and photon sputtering produce a source peaked in the solar direction), and (iv) lunar rotation (4 m s<sup>-1</sup> amplitude, 29.5-day period) effects; see Figure 2.2.

Ip [1991] was the first to model the dynamics of the neutral Na and K exospheres in some detail, and predicted a cometlike structure with gross symmetry about the instantaneous lunar-solar line. He found that such a structure should be characterized by an atmospheric pause toward the Sun caused by radiation pressure reversal of trajectories, and a long, flowing atmospheric tail extending down-Sun behind the Moon. Based on the radiation pressure arguments outlined above, one expects the extent of the lunar Na and K envelopes to “breathe” with both lunar phase and season (the latter due to the Earth’s motion around the Sun). The most extended lunar Na/K atmosphere is therefore predicted for the first, first-quarter Moon of the spring; similarly, the most compact lunar Na/K atmosphere is predicted for the first, last-quarter Moon of the fall. Observations by Mendillo et al. [1991] and Flynn and Mendillo [1993] have borne out these expectations, as have Flynn and Mendillo’s [1995] Monte Carlo modelling effort.

The most complete model of lunar Na and K dynamics to date has been constructed and exploited by Smyth and Marconi [1995a]. Following Ip [1991], these workers produced a Monte Carlo based source distribution; the model calculates the number density, column density, and brightness profiles of Na and K, once an atom is released from the surface, taking into account a full integration of the gravity and radiation pressure terms in the equation of motion; the lunar heliocentric velocity is accurately computed based upon Brown’s theory. All Na and K sources were assumed to be at the surface (i.e., satellite orbits were not included). Gas-gas collisions were ignored, but gas-surface collisions were included, with free parameters being used to explore the effects of varying the surface thermal accommodation and gas-surface sticking coefficients. During trajectory integration the model tracked the atom’s position and turned off radiation pressure terms when the atom was in the Moon’s shadow.

Many useful findings resulted from the exploitation of this model, including certain constraints on source processes which were described in §3 below. Smyth and Marconi’s model (like Flynn and Mendillo’s [1995] model) found it necessary to have a “mildly” nonthermal (i.e., 1000 K) source in order to adequately fit observed Na altitude profiles. Additionally, in order to fit the tailward brightness lobe observed by Mendillo et al.’s wide-field Na imaging project, Smyth and Marconi [1995a] found it necessary to have a Na source flux that is rather sharply peaked around the subsolar point, with a subsidiary maximum over the morning terminator. The application of their model to noble gas dynamics in the lunar

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its perihelion and aphelion, and an even more important velocity-dependent effect of 0.5 km s<sup>-1</sup> amplitude, with a positive extremum in the spring and a negative extremum in the fall.



atmosphere would be worthwhile.

### 3.0 SINKS, SOURCES, AND RECYCLING OF NEUTRAL SPECIES

In this section I synthesize observations and theory in an attempt to describe what is known about the lunar atmosphere's sinks, sources, and recycling mechanisms.

#### 3.1 Loss Mechanisms

Let us begin with loss mechanisms (also called sinks) in part because they are simpler and better understood than the lunar atmosphere's source mechanisms. By discussing sinks first, one additionally provides some important background for the discussion on sources later, in §3.2.

A combination of SIDE measurements [Vondrak et al., 1974] and He gravitational escape rate estimates gives a total loss lunar rate of the atmosphere of  $\sim 10 \text{ g s}^{-1}$ . This high loss rate (compared to the  $\sim 2 \times 10^7 \text{ g}$  total atmospheric mass) implies that losses in effect control the column density and equilibrium abundances of the tenuous lunar atmosphere.

No fewer than four lunar atmosphere loss mechanisms have been identified. I now briefly review the characteristics of each.

*1. Gravitational Escape:* Since the lunar atmosphere is an exosphere, in which the mean free path far exceeds the local scale height, atoms or molecules moving away from the Moon with radial velocities relative to the center of the Moon exceeding the lunar escape velocity, are normally directly lost from the lunar atmosphere.<sup>[23]</sup> Exceptions to this occur if, during "escape," radiation pressure retards the velocity below the local escape speed, a collision reverses the atom or molecule's course, or the atom or molecule is ionized and driven back to the Moon. None of these exceptions is particularly important in the lunar case, and each serves only to perturb the escape flux slightly from its nominal value. Whether an atom or molecule achieves  $v_{\text{escape}}$  depends primarily on its initial speed when it is released from its source, whether that is at the surface or in the atmosphere (e.g., due to photodissociation). As such, the time dependence of the gravitational escape mechanism directly depends on the number-weighted, time dependence of the source mechanisms. Species escaping purely gravitationally become trapped in high Earth orbit, until they are lost due to other processes, such as ionization. However, radiation pressure provides

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<sup>[23]</sup>  $v_{\text{escape}} = 2.38 \text{ km sec}^{-1} (R_M/R)^{1/2}$  (where  $R$  is distance from the center of the Moon); hence,  $E_{\text{escape}} = 0.03 \text{ eV/amu}$ . The escape energy requirements of H, He, Na, and K are 0.03 eV, 0.12 eV, 0.69 eV, and 1.2 eV, respectively. These energies convert to temperatures of  $\approx 340 \text{ K}$ , 1370 K, 7880 K, and 13,700 K.

acceleration to atmospheric species moving anti-sunward down the lunar exospheric tail, enhancing escape rates in this direction, and creating a source of directly escaping species from the Moon to interplanetary space.

*2. Ionization Loss:* Atoms and molecules in the lunar atmosphere that become ionized are generally lost from the system.<sup>[24]</sup> This is because ionized constituents are accelerated beyond escape speed as they travel on the local solar wind electric field. Re-impact and implantation occur for approximately half of the ions created at low altitudes (i.e., where the solid angle of the Moon fills half the sky), but becomes progressively less important with altitude as the solid angle of the “lunar obstacle” decreases. It is important to note, however, that this factor of 1/2 is a time average; at any given time and place the electric field is directed either toward or away from the surface and therefore channels all newly created ions in that direction.

The sources of ionization that are important in the lunar atmosphere are photoionization by solar UV, charge exchange, and solar wind impact ionization. All vary in concert with the 11-year solar cycle, and to a lesser degree with the 28-day solar rotation; solar wind driven charge exchange and electron impact additionally show a significant degree of short-term fluctuation, and are also (unlike photoionization) essentially curtailed during the  $\approx 15\%$  of each lunar orbit when the Moon is within the Earth’s magnetotail. However, for the species and circumstances of interest to us, photoionization is always the dominant (i.e., fastest) ionization process.

*3. Chemical Loss:* Two types of chemical loss occur in the lunar atmosphere. The most important of these is due to collisions with the surface, which can result in chemical reactions leading to an atom or molecule’s bonding to the surface before it is ballistically ejected again. Although this is probably not important for any of the five known lunar atmospheric species, it is believed to be an important mechanism for  $p^+$ , He, and O loss from solar wind impingement on the Moon. Less important is loss to chemical reactions occurring for gas-gas collisions. As discussed above, although the lunar atmosphere is an exosphere, few percent of the atoms resident there do suffer collisions with another atom before being lost to other processes. However, the cross sections for reactions to occur for many lunar species binary collisions (e.g., Ar-X, He-X, Na-Na, Na-K, K-K) are quite low, further reducing the (already low) effectiveness of this loss process.<sup>[25]</sup> There is no important known time variability to chemical losses in the lunar atmosphere.

*4. Condensation:* An important, though usually temporary, loss mechanism from the lunar atmosphere is loss to condensation. Condensation occurs primarily on the lunar nightside

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<sup>[24]</sup> Molecules are also subject to loss by photon- and electron-impact disassociation.

<sup>[25]</sup> Of course, it is possible that highly reactive species could be found among the missing constituents of the lunar atmosphere.

when species transported from the dayside contact the cold surface and become adsorbed in shallow potential wells with lattice residence times comparable to or in excess of the 14-day lunar night. Condensible lunar atmospheric species include Ar, Na, and K, as well as the (still undiscovered but no doubt present) H<sub>2</sub>O from the meteoritic complex. In most cases, species “lost” to condensation are regained after sunrise, and condensation loss should be considered a temporary sink, rather than a permanent one. However, if a condensible finds its way to a permanently shadowed polar cold-trap (e.g., Arnold, [1979]; Hodges, [1991]; Morgan and Shemansky, [1991]), then it may succeed in being permanently lost.<sup>[26]</sup> Condensation loss probabilities are not significantly time variable.

*Comparison of Loss Processes:* Table 3.1 compares the key gravitational and ionization escape timescales for the known lunar atmospheric species, and water vapor. With the exception of He and any H, H<sub>2</sub>, or T>1000 K (“hot”) water, photoionization is always the dominant (i.e., fastest) loss process. Furthermore, the dominant lunar atmospheric loss timescales for each species are short, i.e., hours to weeks, showing definitively that all of the species in the lunar atmosphere are continuously being replenished.

Having said that loss timescales are short, however, it is important to recall the results obtained by observers (e.g., Sprague et al. [1992], Mendillo et al. [1993]) that show the vertical distribution of Na and K in the lunar atmosphere is steeper than the R<sup>-2</sup> distribution characteristic of a freely escaping atmosphere. It is probably also true for Ar as well, and implies that Na, K, Ar, Rn, and any H<sub>2</sub>O are largely bound. Furthermore, for all species except He, the ballistic hop time (minutes to hours, depending on the gas temperature) is short compared to the escape time, indicating that many hops occur before loss. This in turn implies that Na, K, Ar, and other heavies that may exist, like H<sub>2</sub>O, are “recycled” through the surface many times prior to loss. During this recycling process they can experience thermal accommodation and/or re-emission by any of a number of nonthermal source processes, which I now describe.

### 3.2 Source Mechanisms

Let us now turn to a discussion of the sources which feed the lunar atmosphere. The seven sources proposed to date fall into five main categories: (1) thermal, (2) sputtering, (3) chemical, (4) meteoritic, and (5) interior release. Although new species can be produced by chemical reactions on the surface or in near-surface crystal lattices, their ultimate release to the atmosphere must occur through some energetic process, such as thermal desorption, sputtering (including chemical sputtering), or meteoritic impact. Therefore, I do not discuss chemical production as a separate source process for the lunar atmosphere.

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<sup>[26]</sup> The exception to this being if meteoritic impact or Ly $\alpha$ -driven photon sputtering off the interplanetary H results in subsequent release before it can be shielded by regolith turnover.

The interested reader is also referred to the excellent article on by Madey et al. [1998] on laboratory studies of the desorption of alkali species.

Concerning the atmospheric sources themselves, two important facts must be appreciated: (i) Different kinds of source mechanisms are important for different species, and (ii) in general, no single source mechanism supplies all of any given species. Before critically discussing the importance of various sources for each species, I first describe the five source categories just enumerated.

*1. Thermal Sources:* This source, which is sometimes also called *thermal desorption*, involves sublimation from adsorption wells on grains at the “very” (i.e., uppermost layer of the) surface or within the uppermost regolith (i.e., to the depth that is in thermal contact with the diurnal cycle).<sup>[27]</sup> It obviously follows the 29.5-day diurnal cycle, but has little or no annual time dependence (the peak-to-trough solar insolation variation as the Earth moves from its January perihelion to its July aphelion is just 4%). Spatially, this source is concentrated on the dayside, and follows the form  $S_{therm} = C_x / t_{therm}$ , where  $C_x$  is the concentration of species  $x$  on the surface (number per unit area) and  $t_{therm} \approx 1.6 \times 10^{-13} \exp(D/kT)$  seconds is the thermal desorption time. Here,  $D$  is a surface- and species-dependent activation energy usually associated with a well depth (see Hunten et al. [1988]), and  $kT$  is the thermal energy at temperature  $T$ , which owing to  $T$  varies with solar zenith angle, and therefore with local time of day and latitude. The activation energies for Na and K are 0.259 eV and 0.241 eV, respectively; the activation energies of He and O are 0.001 eV and 0.079 eV [Hunten et al., 1988].

In general, the combination of the exponential nature of  $t_{therm}$  and the finite reservoir of gas adsorbed or condensed onto the surface implies that this source is primarily concentrated along the morning terminator, with substantially less strength across the dayside. It has essentially no strength at night, except for noncondensibles like He, H<sub>2</sub>, O<sub>2</sub>, and Ne. Local effects due to varying surface albedo, emissivity, conductivity, and terrain slope will occur. Further, the exponential dependence of this source makes it far stronger in equatorial latitudes than near the poles. This source produces an ensemble distribution set by the weighted average of thermal Maxwellians across the surface. Since the surface temperature maximum on the Moon is near 400 K, this source will produce bound, ballistic atoms (or molecules) which (except for H, He, and H<sub>2</sub>) have scale heights of tens of kilometers or less.

*2. Sputtering Sources:* Sputtering can be defined as the ejection of a species from a lattice site in the upper few monolayers of a surface, owing to the injection of a discrete impulse

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<sup>[27]</sup> I note that the surface area of the grains on the lunar surface is, owing to microphysical roughness, large compared to the spheric surface area of the Moon, enhancing this and other sources that are proportional to exposed surface area.

of energy. Sputtering processes on the Moon have been a subject of interest since returned Apollo samples showed unusual compositions in the rims of grains and glasses [Kerridge and Kaplan, 1978]. The solar wind is known to sputter material from the regolith and to implant material in and around the regolith [Hodges and Hoffman 1975]. Effective yields obtained from the analysis of lunar samples indicates sputtering erosion of  $\sim 0.1\text{--}0.2 \text{ \AA yr}^{-1}$ , or  $\sim 10\text{--}100 \text{ g s}^{-1}$  for the whole Moon (e.g., Arnold [1979]).

All types of sputtering on real (as opposed to simple laboratory situation) surfaces are complex, and little quantifiable information has been developed on yield effects like surface roughness (which lowers sputter yields on real surfaces by factors of a few as sputter products encounter other grains while they attempt their exit to space), grain chemical heterogeneity, sputter site microslope, grain exposure dosage, and surface temperature; these circumstances prevent the easy quantification of sputter yields across the real Moon in space and time.

Several types of sputtering have been discussed in the lunar atmospheric literature; these include: *photon sputtering* (also called photon-stimulated desorption), *charged particle sputtering* (e.g., due to incident, energetic  $e^-$ s,  $p^+$ s, or  $\alpha$  particles), and *chemical sputtering*. Cosmic ray sputtering is not important here because the energy deposition occurs at depth, thereby preventing liberated species from escaping to the atmosphere.

Photon sputtering [McGrath et al., 1986; Morgan and Shemansky, 1991] creates a source which is essentially diurnal in character and concentrated at subsolar latitudes (which of course are seasonally dependent).<sup>[28]</sup> Laboratory studies of photon desorption (e.g., Townsend [1983]; Wiens et al. [1993]; see also the review volume by Johnson [1990]) demonstrate the Maxwellian nature of its source distribution, with characteristic temperatures of  $\approx 800\text{--}2000 \text{ K}$ . This produces a velocity distribution that is intermediate between the thermal source and charged particle sputtering, and which can be moderately coronal, particularly for light species.

Charged particle sputtering (e.g., McGrath et al., [1986]; Johnson and Lanzerotti [1986]; Johnson and Baragiola [1991]) falls off with the cosine of the solar zenith angle, thereby also creating a source which is diurnal in character and concentrated at subsolar latitudes; local effects due to surface temperature and slope perturb this source distribution. Charged particle sputtering produces a Sigmund-Thompson velocity distribution with characteristic speeds of  $1\text{--}3 \text{ km s}^{-1}$ ; such velocities are sufficient to populate both high-altitude coronal

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<sup>[28]</sup> An important exception to this is that  $\text{Ly}\alpha$  photons resonantly scattered off H in the interplanetary medium can and will induce sputtering of species with work functions below 10 eV at night and in the lunar polar regions. *Very* near the poles, and in permanently shadowed regions,  $\text{Ly}\alpha$  sputtering can dominate direct solar sputtering for some species (see Morgan and Shemansky [1991], including  $\text{H}_2\text{O}$  ice.

trajectories and (for  $v > 2.38 \text{ km s}^{-1}$ ) hyperbolic, direct escape orbits. Importantly, the solar wind charged particles that normally dominate the incident flux driving this source cannot reach the Moon during the few days each month when the Moon is within the Earth's magnetotail; the only available sources of charged particles during that time are electrons and ions trapped in the terrestrial magnetosphere.

*3. Chemical Sources:* Chemical sputtering (see Roth [1983] for background on this process, or Potter [1995] for a short overview) results when a chemical reaction on the very lunar surface (e.g., due to incident solar wind protons) has sufficient excess energy to desorb (as opposed to lattice-eject) an atom or molecular fragment onto a ballistic trajectory. This process appears to offer both high yields for sputtered volatiles, and an at least partially accommodated thermal velocity distribution. Because exothermic reactions are required, it would not apply to noble gases. Chemical sputtering is much more temperature dependent than either photon or charged particle sputtering, because there is no photoelectric effect minimum energy to overcome; instead, there is a simple  $\exp(D/kT)$  type activation barrier (again,  $kT$  is the thermal energy for a temperature  $T$ , with  $k$  being the Boltzmann constant). Chemical sputtering yields for relevant surface materials appear to peak in the 500–1000 K temperature range [Potter, 1995], and recent work on the variation of Na abundance with solar zenith angle [Potter and Morgan, 1998] provides some intriguing evidence that chemical sputtering may play a significant role with regard to lunar Na production; this is discussed at the end of this section.

*4. Meteoritic Sources:* Meteorite impacts onto the lunar surface at velocities above a few  $\text{km s}^{-1}$  (the average lunar meteorite impacts at  $v \approx 15 \text{ km s}^{-1}$ ) produce both a cloud of impact-generated vapor and a source of hot or even molten surface material that will subsequently outgas until it cools. In both cases, the yields of various species depend on the energetics of the collision (and therefore the meteor velocities), on the composition of the target site and the impactor, and (to a lesser degree) on the surface temperature, rock/soil ratio, and compaction state. Discussion of the lunar meteoritic source can be found in papers including Morgan et al. [1989], Morgan and Shemansky [1991], Sprague et al. [1992], and Smyth and Marconi [1995a], and in observation reports by Hunten et al. [1991], Cremonese and Verani [1997], and Verani et al. [1998].

The meteoritic source is the average over all impacts, which each produce a localized source for each species  $x$  of the form  $S_{met}(x) = C_x V_x \eta$  where  $C_x$  is the weighted average concentration of  $x$  in the heated target and impactor material,  $V_x$  is the vapor production rate of species  $x$  in the heated material, and  $\eta$  is the fraction of vapor that escapes to the atmosphere. The temporal variation in this source (above the essentially constant background rate) is set by the crossing of the Earth and Moon through debris fields left in orbit by comets (so-called comet trails) and Earth-crossing asteroid collisions, with various well-known examples such as the Perseids occurring at predictable times each year. The

strength of each “shower” depends on several factors, including where and at what velocity the Earth’s orbit intersects the debris trail orbit, and can vary from year to year (the interested reader is directed to the relevant papers in the review volume by Rettig and Hahn [1996]).

Because the debris trails have space cross sections that are orders of magnitude larger than the Moon, the resulting lunar source is spatially uniform on the velocity-forward hemisphere encountering the shower, and sharply curtailed on the shadowed hemisphere. The yield of vapor directly produced by meteoritic impact is somewhat uncertain, and will be ameliorated by local macroscopic and even microscopic roughness effects as species exit the impact site. Vapor escaping the impact site will display a Maxwellian temperature distribution with characteristic temperatures of 2000–5000 K (e.g., Ahrens and O’Keefe [1971]; Eichorn [1978]). Vapor produced subsequently by the outgassing of solid and melt material at the impact site will produce a weighted-average Maxwellian with temperatures ranging up to perhaps 3000 K. The meteoritic source will therefore produce both bound and directly escaping species. Vapor produced by the impact of secondaries (i.e., at velocities  $<2.4 \text{ km s}^{-1}$ ) will be colder than the vapor produced at the primary impact site. In general, atomic neutrals from the meteoritic impact source are expected to be dominated by volatile species such as alkalis, and sulfur, with molecular fragments due to metal oxides,  $\text{H}_2\text{O}$  (particularly for an icy impactor or an impact site in a polar cold-trap), and other species appearing primarily as molecular fragments. As noted by Morgan and Killen [1996], the presence of refractory-rich grain coatings containing Al, Si, and Ca in lunar samples provides evidence that the most volatile components of the meteoritic vapor are preferentially lost to the atmosphere.

Cremonese and Verani [1997] reported a significant Na brightness enhancement (to 3.4–5 kR between 100 and 500 km altitude in  $\text{D}_2$  emission alone) during the Leonid meteor shower of, 1997. Their observed brightness enhancement translates into unprecedented abundance and scale height increases of the lunar atmosphere. However, the statistical correlation of this event with the Leonids (like the Hunten et al. [1991] report associated with the Geminids) is not very strong, and requires corroboration.

*5. Internal Release Sources:* Gases (e.g., radiogenic products, like  $^{40}\text{Ar}$ ) can be released from the Moon by *vulcanism* (e.g., Taylor [1982]), *crustal diffusion* (e.g., Killen [1989], Sprague [1990]), or *seismically induced seepage* [Hodges et al., 1973]. Vulcanism is not important today, but may have been important in the distant past (see §5.2). Killen’s work has shown that crustal diffusion is not important for the Moon’s Na and K, and I find no reason it should be for any nonradiogenically produced species. Turning to seismically induced seepage, the network of Apollo seismic stations that reported data for over 6 years established that the Moon is essentially inactive, at least on those timescales, with only very minor ( $10^{7-9}$  erg), tidal, stress-driven events having been observed from the interior

(see Taylor [1982], and Kaula et al., [1986]). In this regard, Hodges and Hoffman [1975] have reported a correlation between these stress-driven seismic events and Ar releases detected by the Apollo 17 LACE surface mass spectrometer, and Rn production has been found to be correlated with the mare/highland boundaries [Gorenstein et al., 1974].

### 3.3 Species-by-Species Sinks, Sources, and Recycling

Let us now move from a discussion of the general attributes of each sink and source, to a species-by-species discussion of which sources and sinks dominate. In doing this, it is useful to make the now well-established distinction between *primary source* atoms and *recycling source* atoms, where the primary source(s) is/are responsible for initially liberating the constituent from the surface to the atmosphere, and the recycling source(s) is/are responsible for subsequent releases after each ballistic recontact with the surface [Sprague et al., 1992]. This in mind, I now briefly discuss the sources of lunar atmospheric species.

*Radon and Polonium:* As summarized in §1.4, alpha particles resulting from the radioactive decay of  $^{222}\text{Rn}$  and  $^{210}\text{Po}$  were discovered and monitored by orbiting  $\alpha$ -particle spectrometers aboard the Apollo 15 and 16 Command Service Modules. The primary source of these radioactive daughter products must be internal release. Owing to their short half-lives, 3.8 and 138 days, respectively, as well as the 21-year half-life of the  $^{210}\text{Pb}$ , the parent of  $^{210}\text{Po}$ , it is also clear that this outgassing must have both been active during the Apollo missions, and have been ongoing for some time—presumably, it is quasi-continuous.

An important characteristic of the Apollo observations was the spatial association of Rn and Po with specific (though differing surface) sites, such as the craters Aristarchus and Grimaldi (for Rn) and over mare/highland unit boundaries (for Po), that was reported [Bjorkholm et al., 1973; Gorenstein et al., 1973, 1974]. Once released from the Moon as gases, Rn and Po will each diffusively transport across the surface<sup>[29]</sup> until they are ultimately lost to either photoionization or radioactive decay; typical  $T=400$  K daytime ballistic hop lengths and altitudes will be of order 10 km and 3 minutes.

In Apollo observations, both Rn and Po were detected in highly localized,  $\sim 150$  km-wide bins which are small relative to their expected (many hundreds to  $>1000$  km) transport lengths prior to  $\alpha$  decay. Despite its 138-day half-life, Po was found only in localized concentrations near the edges of maria, indicating primary emission sources of significant contribution were detected. However, the localized detection of Rn was probably due to the fact the emission sites detected by Apollos 15 and 16 were in darkness, and were therefore cold at the time they were observed. Heymann and Yaniv [1971] gave a prediction of

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<sup>[29]</sup> Rn is a noble gas and is therefore quite volatile; Po's volatility is of the same order as Na.



localized emission for just this reason, prior to the first Apollo Alpha Particle Spectrometer (APS) flight.<sup>[30]</sup> Thus, the detected Rn, which is condensible on the cold nighttime surface, was almost certainly released since nightfall and was found plated out near its source. One of course also predicts that a thermally driven Rn recycling source is important on the dayside, but this has not been observed.<sup>[31]</sup>

*Helium:* As described in §1.4, neutral  $^4\text{He}$  was detected and monitored by the Apollo 17 LACE mass spectrometer during its 9-month (10-lunation) operational life.

The good agreement between LACE measurements, and exospheric transport models using known He source rates from the solar wind, led Hodges and Hoffman [1975] to conclude that the primary source of the  $^4\text{He}$  is solar wind  $\alpha$  particles encountering the Moon at a typical rate of  $\sim 1\text{--}3 \times 10^{24} \text{ s}^{-1}$ . On impact these are either neutralized (at typical energies of 4 KeV), or later released as neutralized  $^4\text{He}$  from the solar wind that was earlier-implanted and subsequently neutralized in grains. The case for a solar wind primary source is also supported by significant correlations of He abundance with solar wind momentum flux [Hodges and Hoffman 1974, 1976].<sup>[32]</sup> Hodges [1975] reported that the fraction of escaping radiogenic He is thought to be the same as that for  $^{40}\text{Ar}$ , i.e.,  $\approx 10\%$ . This leads to a radiogenic He loss rate of about  $10^{23} \text{ atoms s}^{-1}$ , which is about 10% of the solar wind alpha particle flux.

Because LACE could only obtain measurements at night, when the instrument and the site around it were in fact shielded from direct solar wind, typical He atoms detected by LACE must have been transported to the nightside and suffered recycling after of order 10 re-collisions with the lunar surface (recall, He is noncondensable). The probability of a He atom's ionization loss after 10 ballistic hops (0.2 days) is negligible, but at 400 K, He Jeans (i.e., thermal leakage) escape losses are nonnegligible (the escape time is comparable; see Table 3.1).<sup>[33]</sup> Hodges and Hoffman [1975] and then Hodges [1975] reported that their He abundance measurements with LACE were about 60% of the values their model predicted

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<sup>[30]</sup> These workers also predicted the possibility of a sunrise terminator peak, which may have been too weak for the Apollo orbital instrumentation to detect.

<sup>[31]</sup> A sputter recycling mechanism can also be envisioned, but owing to the order of magnitude higher mass of Rn and Po, compared to Na and K, an equivalently energetic process would produce an  $\sim 10$  times more compact corona, extending out only to  $\sim 1R_M$ .

<sup>[32]</sup> The transport time for He over a characteristic distance of  $R_M$  is of order 0.2 days. It is unfortunate that the  $K_p$  records available to LACE investigators were only daily averages. The correlation with the solar wind source through  $K_p$  would be better proven if a change in He abundance were seen after a delay by a characteristic transport timescale following a change in  $K_p$ .

<sup>[33]</sup> Escaping He atoms are primarily ( $>90\%$ ) lost to orbit around the Earth, where they typically survive for 6 months before being ionized [Hodges, 1978].

should be found. This led them to conclude that  $\sim 40\%$  of the solar wind He impacting the Moon escapes at high velocity, either through spectral reflection of incident alpha particles off the surface, or through suprathermal release of He trapped within (at 4 KeV incident energies) soil grains (e.g., meteoritic, sputtering, etc.).

To summarize, it seems clear that the primary source of lunar atmospheric He is the solar wind, but perhaps 10% is due to interior outgassing [Hodges, 1975]. The  $\sim 40\%$  He loss noted by Hodges and Hoffman during nightside measurements indicates some recycling loss, which is probably due to a combination of the initial reflection of neutralized  $^4\text{He}$  off the surface, and later nonthermal emission from grains, and Jeans losses. It is unfortunate that the LACE instrument was not equipped to measure the energetics of the neutral species it detected.

*Argon:* As described in §1.4, argon was detected by the Apollo 17 LACE instrument. About 90% of the argon detected was  $^{40}\text{Ar}$ , which results from the decay of  $^{40}\text{K}$  and therefore must ultimately be derived from the lunar interior, its primary source. (In contrast, the  $^4\text{He}$  LACE detected is primarily derived from the solar wind, as described above.) The remaining  $\sim 10\%$  of the LACE argon signal was  $^{36}\text{Ar}$ , for which the parent source is the solar wind. LACE data indicate that the  $^{40}\text{Ar}$  source rate is variable, suggesting that the release rate of Ar from the lunar interior is not steady. The average loss rate of Ar from the lunar atmosphere is about  $1.5\text{--}2 \times 10^{21}$  atoms  $\text{s}^{-1}$  [Hodges, 1975]. Hodges et al. [1973] and Hodges and Hoffman [1975] argued for a correlation in tidal, stress-driven moonquakes and Ar release rate, but owing to the failure of the LACE mass spectrometer after only 9 months of operation, the available database is too small to firmly prove this attractive suggestion.

The fact that LACE did detect an Ar wind blowing across the terminator (when LACE was still in darkness and its local surface site was still cold) provides direct evidence to support one's expectation that thermally desorbed Ar that is condensed on the nightside (where the probability of adsorption is  $\sim 30\%$  and the mean thermal desorption time is  $\sim 1$  day; Hodges, 1975] is released and recycled onto the dayside through ballistic transport and thermal reaccommodation, prior to its ultimate loss by photoionization (after a characteristic exposure time of 25 days; see Table 3.1).<sup>[34]</sup> Hodges [1975] reports that the average Ar lifetime on the Moon is  $\approx 100$  days, of which 80% is spent adsorbed on the lunar surface. As to nonthermal recycling sources, there is no clear indication of whether any nonthermal, coronal distribution of Ar exists because LACE was not capable of measuring the energetics of the argon atoms it detected (but see Flynn's [1998] suggestion).

*Sodium and Potassium:* Observations of Na and K were reviewed together in §1.6. Owing

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<sup>[34]</sup> The fact that this exposure time is so short provides convincing evidence that  $^{40}\text{Ar}$  is being released from the Moon continuously or quasi-continuously.

to the fact that these species are both alkalis, and to the relative paucity of K data sets compared to Na data sets, I will restrict this discussion here to Na, but one should keep in mind that the same findings may well apply to K.

As I will describe, much controversy exists in the literature as to the relative importance of various source mechanisms for Na, and I will devote more space to Na sources than to any other lunar atmosphere species. This is of course ironic, since Na and K are only minor species compared to the other known atmospheric constituents, and have far fewer geophysical implications than do lunar atmospheric He, Ar, and Rn. Still, the great mass of diverse data sets collected on Na (and K) since, 1986 provide more grist for discussion than is possible for other atmospheric constituents, and there is a large literature on this topic.

I begin by assessing the native reservoir of the Na observed in the lunar atmosphere. From its mass ( $\sim 10^3$  g), a 50% day/night diurnal cycle, and sodium's lifetime in sunlight ( $\approx 14$  hours), one can compute that the present lunar atmosphere must be supplied with Na at an average rate of  $\sim 10^{-2}$  g s $^{-1}$ ; taking into account the time average 50% return of ionization losses to the surface [Manka and Michel, 1971], this implies that over the age of the solar system some  $\sim 10^{15}$  g of Na has been lost from the Moon, and therefore has been supplied from native reservoirs. The estimated uncertainties in this estimate are of order factors of several, and are dominated by the uncertainty in Na's photoionization lifetime. Taking the average Na abundance in lunar soils (0.33% in highland crust, 0.06% in the bulk Moon; Taylor, 1982], this corresponds to the depletion of a regolith layer of 0.5 cm to perhaps 5 cm deep, which is less than or comparable to a sputter-erosion depth of the lunar surface over the past 4 Gyr.

How is this Na initially injected into the atmosphere? Smyth and Marconi [1995a] have provided an excellent discussion demonstrating the wide range of rate uncertainties for the meteoritic, photon sputtering, and solar wind sputtering mechanisms. Their discussion demonstrates that even the average production rates for Na due to sources are too uncertain to allow us to distinguish between various candidate mechanisms on the basis of source rate considerations alone.

Both casual and the dedicated readers of the literature will find many contradictory conclusions and even contradictory data sets concerning the primary (or direct) source of Na. This situation is clearly exacerbated by real time variability in the solar wind, solar UV, and the meteoritic complex, as well as by relatively sparse sampling of a complex environment, and the "unfortunate" fact that *both* the primary and recycling source Na are seen in every observation.<sup>[35]</sup> <sup>[36]</sup> What is clearly lacking is a long (e.g., several lunation)

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[35] If only God would paint the atoms differently so we could tell which is on which team!

[36] For example, near the limb the air mass projection factor for Na,  $\sqrt{2\pi R_M/H} \sim 6-15$ ,

time base of densely sampled measurements at various latitudes.<sup>[37]</sup> Of course, even such a wonderful data set would have difficulties associated with the deconvolution of the Na line-of-sight observational path integral into a 3-D distribution. Truly the best experiment would involve a lunar orbiting spacecraft making Na and K measurements via both mass spectroscopy and spectroscopic tomography, all the while monitoring solar wind, solar UV, and meteoritic fluxes.

Since the prospect for either of the two data sets just described is not good on a timescale commensurate with the completion of this review, and may in fact be many years away, I will simply say what appears to be the case about the primary Na source mechanism(s), ordering the points in descending order of confidence in them:

- Both thermally accommodated and suprathreshold Na have been widely observed by spectroscopy and imaging experiments.
- Several primary source mechanisms no doubt operate. These include meteoritic release, thermal desorption, and both photo- and charged particle sputtering. The debate is about their relative importance in space and time.
- The relative importance of these sources is spatially dependent, following surface compositional trends, topographic factors (e.g., steep slopes), latitude, and solar zenith angle.
- The relative importance of the sources is temporally dependent on both lunar diurnal cycles and longer timescales.
- Some potential sources can be ruled out as being of widespread importance for Na production; these include internal outgassing/diffusion of Na from the regolith, and surface chemical reactions.
- Of the viable sources, only the meteoritic source likely operates to any significant degree on the lunar nightside or very close to the poles.
- The steep solar zenith angle dependence of the Na coronal-component brightness indicates that, while meteoritic effects may be important for bringing Na to the very surface where it can be released, it cannot realistically be the dominant Na release mechanism on the dayside.

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implying that >80% of the Na atoms observed are actually foreground or background Na far removed from the surface.

<sup>[37]</sup> Additionally, it would be useful to obtain Na abundances over the lunar terminator, which would be useful for gauging how much condensed Na is thermally desorbed from the nightside surface on sunrise.

- The steep subsolar dependence of the Na brightness on subsolar latitude indicates that, of the viable sources that produce nonthermal production, neither meteoritic production nor simple desorption is dominant. The data are, however, consistent with a chemical sputtering source, as demonstrated by the nice fit of  $\ln(I_{\text{Na}}/\cos(\chi))$  with  $T$  [Potter and Morgan, 1998]. The difficulty with this hypothesis is that Na chemical sputtering is thought to be efficient only at significantly higher temperatures than the 400 K typically attained on the lunar surface.<sup>[38]</sup>
- The lack of a turnoff in Na abundance observed during observations in the terrestrial magnetotail (e.g., Mendillo et al., [1999]), which shields the Moon from solar wind bombardment, and therefore much (but not all) of the energetic charged particle flux, favors photosputtering (also called photon-stimulated desorption in the literature); however, because the magnetotail is not a perfect shield (see Lin et al., [1977] for Apollo data, and Potter and Morgan [1994] for a discussion with respect to Na), charged particle sputtering sources must operate at some level, at least part of the time.

Taking these points together, it appears that either photon sputtering or chemical sputtering is the most likely mechanism for generating the dominant amount of dayside lunar Na. However, meteoritic effects and charged particle sputtering must also play a role. Notably, meteoritic effects must play at least an indirect role, by bringing fresh Na to the surface via regolith turnover (and direct Na import in impacts). The meteoritic source also no doubt dominates on the dark side, and possibly globally (in terms of total Na release) during discrete showers. Charged particle sputtering must play a secondary role.

Unless the loss rates for Na have been significantly underestimated, the ensemble average production of the operating Na sources must be inefficient. This may relate to why the Na coronal gas temperature derived from scale height data appears low compared to temperatures expected from laboratory photon sputtering data (see Johnson [1990]).

I now briefly turn to the subject of recycling sources for neutral sodium. Kozłowski et al. [1990] first postulated a recycling mechanism that could explain the apparent two temperature components of the K atmosphere. This concept was dubbed “*competing release mechanisms*” by Sprague et al. [1992]; Figure 3.1 depicts the postulated recycling processes. At its core, the competing release mechanisms approach identifies the fact that several sources are at work and that they have different spatial and temporal dependencies.

In this scenario, which clearly represents the spirit of the rich variety of physical processes at

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<sup>[38]</sup> However, it may be that in some places surface temperatures reach 500 K or higher (i.e., grains on or on top of rocks with low emissivity, or localized sites with nearby crater or mountain walls to add flux and create a hotter local surface).

work, atmospheric sodium atoms are divided into several populations: source, ambient, and those adsorbed on surface grains. Table 3.2 gives surface residence times for Na. Atoms on the surface are either thermally desorbed or removed by photodesorption; photosputtering is not shown here, but as described above, more recent results indicate it needs to be. Atoms that have been thermally desorbed compose the thermal component. A similar scheme was discussed by Smyth and Marconi [1995a], using the terminology “direct source” for what we call the primary source, and “delayed source” or “ambient atoms” for what we call here the “recycled source” (see Figure 2.1). The details of the transport and loss of such a population have been reviewed above in §2 and §3.1. The salient point I wish to make here, as did Sprague et al. [1992], is that only a small fraction, perhaps <10%, of the Na atoms observed at any given time in the lunar atmosphere are *truly* source atoms, the others all participating as part of recycling processes.

#### 4.0 COMPARISON TO OTHER SURFACE BOUNDARY EXOSPHERES

As I noted in §1, the Moon belongs to a broad class of bodies with a type of atmosphere known as a surface boundary exosphere [SBE). In an SBE, energetic atoms and molecules removed from the surface have only a small probability of suffering a collision before escaping to space. SBEs are scientifically interesting in part because of the intimate chemical and physical connection between the planetary surface and the atmosphere.

Given the standard definition of an exosphere (i.e., scale height less than the collisional mean free path) and a canonical  $\sim 10^{-15}$  cm<sup>2</sup> collisional cross section for atom-atom collisions, one can quickly derive the fact that for  $R \sim 1000$  km bodies, the distinction between SBEs and collisional atmospheres occurs at surface number densities near  $10^8$  cm<sup>-3</sup>, assuming temperatures near 400 K and species with molecular weights of 10–40.<sup>[39]</sup> The lunar atmosphere’s surface number density maximum, just below  $10^6$  cm<sup>-3</sup>, firmly establishes the lunar atmosphere in the SBE regime.

SBE atmospheres are expected to share certain common attributes, including weak to negligible interspecies communication via collisions, low thermal inertia, short response timescales, low optical depth to sunlight (though optically thick lines may develop), and embedded surface boundary ionospheres.

The processes that generate the lunar atmosphere— namely photon and charged particle sputtering, meteoritic bombardment, solar wind implantation and release, and even weak interior gas release— are common across the solar system, and are expected to play key roles in many SBEs. As such, one fully expects to find SBEs with a wide range of total

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<sup>[39]</sup> For smaller,  $R \sim 100$  km class satellites and icy outer solar system bodies like the Centaurs (see Stern and Campins [1996]), this boundary occurs near  $10^7$  cm<sup>-3</sup>.

masses around many planetary satellites and asteroids.

Although few searches have taken place for SBE atmospheres, spectroscopic line emission detections have taken place at Mercury (Potter and Morgan [1985]; Brown and Yung [1976]),<sup>[40]</sup> and Europa [Hall et al., 1995; Brown and Hill 1996]. No neutral gas has as yet been detected around Callisto. However, at Ganymede there is evidence for both an ionosphere [Gurnett et al., 1996] and a H exosphere [Barth et al., 1996]. Additionally, evidence for sputter products from the surfaces of the Martian satellites has been detected in Mars orbit, indicating the Martian satellites may harbor their own unique SBEs as well. A concise and well-organized review on the atmospheres of the four Galilean satellites has recently been made available by Ip [1997].

As I have just noted, SBEs have been firmly detected around four solar system bodies to date.<sup>[41]</sup> Three of these SBEs— those surrounding Mercury, the Moon, and Io— can be grouped as “*refractory-surface SBEs*” by virtue of the composition of the surfaces of these parent bodies; one expects that SBEs around asteroids would fall into this group as well. The SBE around Europa, however, is more properly classified as a “*volatile-surface SBE*” by the nature of Europa’s ice surface, and one expects that this class of SBE is common in the outer solar system. Beyond this simple classification, other subcategories also no doubt arise; e.g., whether the parent body has a significant dipole magnetic field (as Mercury, Io, and Europa do) or not (e.g., the Moon), whether or not the parent object is embedded in a planetary magnetosphere inducing significant charged particle bombardment onto the parent body’s surface, or whether (as in the case of the four known SBEs) or not (e.g., in the case of weakly outgassing comets and small asteroids with  $R < 10$  km) gravity plays a significant role. Table 4.1 provides some useful comparisons between the known SBEs of the solar system.

I now provide a brief review of the European SBE, and then a considerably more detailed comparison of the lunar atmosphere to its closest analog among the discovered SBEs of the solar system: Mercury’s.

#### 4.1 Europa’s SBE

The presence of a tenuous atmosphere surrounding Europa has been long suspected and discussed in the literature (see the reviews in Burns and Matthews [1986]). However,

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<sup>[40]</sup> Io’s situation is certainly unique, in that the atmosphere contains strong pressure and abundance gradients, with some regions clearly in the SBE atmosphere regime, but others in the thicker collisional atmosphere regime.

<sup>[41]</sup> Note that the surface number densities at the base of Pluto’s atmosphere and Triton’s, roughly  $10^{15}$   $\text{cm}^{-3}$ , firmly establish their atmospheres as “conventional” collisional atmospheres, rather than SBEs.

indisputable evidence for this atmosphere was only obtained when Hall et al. [1995] and then Brown and Hill [1996] spectroscopically discovered gaseous O and Na, respectively,<sup>[42]</sup> with O vastly dominating Na in abundance. The O neutrals detected by Hall et al. [1995] surrounding Europa are comparatively cold ( $T \sim 200\text{--}1000$  K) and at least partially gravitationally bound, as is indicated by its moderate,  $\sim 100$  km scale height. Europa's atmospheric O is thought to be derived from sputtering of H<sub>2</sub>O surface ice by energetic, Jovian magnetospheric ions (see Johnson [1990]); but a fraction of it may also be derived from the photolysis of sublimated H<sub>2</sub>O and, more importantly given the low H<sub>2</sub>O sublimation rates on Europa's 120 K surface, from impact vapour.

In analogy to the lunar case, Europa's atmosphere contains distinct gas populations with different origins and energetics. The differences between Europa's O and Na SBEs can be briefly summarized as follows: In contrast to its O exosphere, Europa's Na exosphere clearly has a more energetic population, with emission having been detected as far as  $25 R_{\text{Europa}}$  from the satellite. The total mass of O in Europa's atmosphere exceeds the Na mass by a ratio of 300:1. Furthermore, whereas Europa's O exosphere is thought to be derived from European H<sub>2</sub>O ice, Europa's Na is suspected to be Ionian in origin, having been transported to Europa in Jupiter's magnetosphere, temporarily implanted in Europa's surface, and then re-released due to energetic particle sputtering.

## 4.2 Mercury's SBE and Its Relationship to the Moon

The closest available analog to the lunar atmosphere is the similarly tenuous SBE of Mercury. Let us begin by briefly summarizing the main attributes of Mercury's SBE. I then compare these attributes, as well as the circumstances that affect Mercury's SBE, and the physical processes at work there, to the lunar case. Unfortunately, space limitations prevent us from undertaking more than a cursory discussion; readers interested in a wonderful discussion of Mercury's atmosphere are referred to the long review by Hunten et al. [1988], the more recent but shorter review by Hunten and Sprague [1997], and the subsequent research papers cited in the final paragraph of this subsection.

*Compositional Overview:* After numerous unsuccessful attempts to detect an atmosphere surrounding Mercury by groundbased methods, UV instruments aboard the Mariner 10 multiple Mercury flyby mission succeeded in discovering Mercury's atmosphere. As described by Broadfoot et al. [1974] and Broadfoot [1976], Mariner 10's ultraviolet spectrometer detected neutral atomic H, He, and probably O. Of the three species, oxygen is probably the most abundant, with  $n \approx 4 \times 10^4 \text{ cm}^{-3}$  near the surface (see Table 4.2). Other UV measurements set upper limits on CO, H<sub>2</sub>, H<sub>2</sub>O, Ne, Ar, Xe, and C abundances in the

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<sup>[42]</sup> Similar searches for Na around Ganymede have yielded only upper limits [Brown, 1997], indicating that Ganymede's Na column must be depleted by a factor of at least 13 relative to Europa.



daytime atmosphere (see Broadfoot et al. [1976]).

Later, in the mid-1980s, both Na and K neutrals were discovered [Potter and Morgan, 1985].<sup>[43]</sup> It was this discovery of Na and K at Mercury that motivated searches for and the discovery of the same species at the Moon two years later. Sprague et al. [1993] and Sprague et al. [1996] have reported searches for both Ca and Li, but obtained only upper limits. Table 4.2 summarizes the species detections in Mercury's atmosphere, and compares these to lunar abundances of the same species.

Ultraviolet occultation measurements by Mariner 10 also set a strict upper limit of  $10^{-12}$  bar on the total atmospheric surface pressure near the terminator, corresponding to a number density upper limit of  $10^7 \text{ cm}^{-3}$  at  $T=500 \text{ K}$ . The Mariner 10 surface pressure upper limit allows for about 100 times the total number density that is present in the combined inventory of species detected to date. Given this, and the relatively incomplete state of sensitive searches for other species, one would find it surprising if other neutral species were not present in the Mercurian SBE.

*Vertical and Lateral Distributions:* Mariner 10 established that the vertical distribution of daytime He above the subsolar region of Mercury appears to be nicely fit by a monothermal distribution with  $T=575 \text{ K}$ . However, the vertical distribution of H apparently requires both hot ( $T \approx 420 \text{ K}$ ) and cold ( $T \approx 110 \text{ K}$ ) components. Puzzlingly, the cold H component is colder than the surface under the measurement! Does this suggest a nightside source?

In contrast, groundbased studies reveal that the daytime Na and K atmospheres exhibit  $T \approx 500 \text{ K}$ , but extended, nonthermal components may also exist [Hunten, 1992]. In this regard, one might ask whether Mercury has a large, faint extended Na coma like that of the Moon, and the answer appears to be yes. Monte Carlo codes developed and explored by Ip [1993] and Smyth and Marconi [1995b] indicated several years ago that it is possible to generate such an extended coma with source rates consistent with what is required to maintain the observed Na emissions at Mercury. Recently, Potter and Morgan [1997] have obtained Na images showing evidence for such an extended coma.

Turning now to lateral distributions, one expects a distinction between condensible and noncondensable species as there is in the lunar atmosphere (see §2). Thus, He, which is not condensable, should be approximately conserved according to the standard  $nT^{-5/2} = \text{constant}$  exospheric conservation law (as in the case for the Moon), and the other known species, all of which are condensable, should show daytime maxima and nighttime cold-trapping. However, the situation is more complex than this, as evidenced by the fact that Mariner 10 data clearly showed that He does not follow the  $nT^{-5/2} = \text{constant}$  exospheric theory.

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<sup>[43]</sup> One should note the far higher abundance of Na and K in Mercury's atmosphere than in the Moon's.

Specifically, whereas the  $nT^{-5/2}=\text{constant}$  law predicts a night/day density asymmetry of 150, Mariner 10 data show that only a 50:1 density asymmetry exists. This difference is likely due to uncertainties in understanding the interaction of He gas with Mercury's surface, probably implying that He's thermal accommodation to the surface is inefficient [Smith et al., 1978; see also Hunten et al., 1988].

Turning to Na and K, for which only daytime data exist (since they are detected by resonance fluorescence), strong (e.g., 5:1) morning/afternoon abundance variations have been reported [Sprague et al., 1996, 1998]. There are also fascinating observations of localized Na and K spatial variations (the so-called Na and K "clouds," sometimes occurring in north-south pairs) seen at high latitudes over the past several years (Potter and Morgan [1990]; Sprague [1990]; Sprague et al. [1997, 1998]. The root nature of these features has not been firmly established, but solar UV, Mercury magnetospheric/auroral [Potter and Morgan, 1990], and local surface concentration enhancements (perhaps associated with radar bright terrains that may even be sources of vulcanism; Slade et al., 1992; Butler et al., 1993] have been suggested.

*Sources and Sinks:* As in the classic picture of any SBE, the abundance and distribution of the constituent species in Mercury's atmosphere must be controlled by a balance between sources and sinks, as modified by surface recycling interactions, and dynamical effects (e.g., gravity, radiation pressure) during transport. Detailed knowledge about this interplay is severely limited at Mercury, owing to the paucity and limited resolution of available observational data sets. Further uncertainties about the nature and composition of Mercury's surface, the meteoritic environment at Mercury, and the detailed structure and variability of Mercury's magnetosphere (e.g., Goldstein et al. [1981]; Ip [1993] exacerbate this situation. Despite these limitations, however, some qualitative information is available.

Concerning sources, it is clear that the ultimate source of much of Mercury's atmospheric H must be the solar wind, but H and O are probably also derived from the photodissociation of H<sub>2</sub>O imported by the meteoritic complex and (rare) cometary impacts. Mercury's He must be supplied by some combination of solar wind capture and internal outgassing. Na and K must be derived from a combination of surface release and meteoritic import. However, the relative importance of charged particle sputtering, chemical sputtering, thermal desorption, photon sputtering, and meteoritic impact is essentially unconstrained (and likely to be highly time variable). An excellent discussion of the current state of knowledge/ignorance in this area has been given by Potter [1995].

Loss processes for the gases in Mercury's SBE include photoionization, photodissociation (for molecules, if present), Jeans escape (particularly important for H and He), and radiation pressure loss. Concerning radiation pressure, it is important to point out that

Mercury’s elliptical orbit drives a strong and complex cycle of both distance and velocity effects that contribute to strong effective photon intensity, and therefore radiation pressure variations (e.g, Ip [1986]; Smyth [1986]; Smyth and Marconi [1995b]). Early on, Potter and Morgan [1987] confirmed such suspicions observationally by demonstrating that Mercury’s Na column is inversely proportional to the instantaneous radiation pressure felt by Na atoms as Mercury travels along its orbit.

*Comparison to the Lunar SBE:* As one compares Mercury to the Moon, one sees both similarities and differences. Somewhat similar rosters of species have been detected in both SBEs, but as shown in Table 4.2, the abundances of all known atmospheric constituents are higher at Mercury (note also that Mercury’s H and O have no observed counterpart at the Moon).<sup>[44]</sup> So too, as shown in Table 4.3, the Na/K ratios at Mercury are significantly higher than those in the lunar atmosphere. These higher abundances, combined with the fact that neutral lifetimes are much shorter on Mercury than on the Moon, provide strong circumstantial evidence that source rates must be higher at Mercury, and/or the recycling processes more effective.<sup>[45]</sup> Yet another similarity is that both the lunar and Mercurian SBEs show strong temporal and spatial variability, but this is not surprising given the tenuous, low-inertia nature of SBEs in general.

Relative to the lunar case, the physics that drives Mercury’s atmosphere is strongly modified by a combination of Mercury’s higher gravity, its closer position to the Sun (affecting thermal conditions and incident photon fluxes), its order-of-magnitude more severe orbital distance and velocity variations, and particularly fundamentally, by the presence of a planetary dipole field and its consequent magnetosphere. As an example, Mercury’s close-in orbit increases solar photon fluxes by roughly an order of magnitude compared to the lunar case, thereby shortening the dissociation timescales for any parent molecules, thereby more quickly transforming such species into daughter fragments, then atoms, and, ultimately, ions. Since typical molecular lifetimes against UV photodissociation are only a few hours at Mercury, molecules are expected to be rare unless they can be rapidly replenished by a strong, ongoing source.

Mercury’s higher gravity results in a shorter time of flight for bound atoms on ballistic trajectories between encounters with the surface. A consequence of this is that an atom experiences fewer encounters with solar photons during each ballistic hop. This, and the shorter lifetimes against photoionization resulting from Mercury’s smaller heliocentric distance, serve to counteract the higher radiation pressure forces on atoms at Mercury.

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<sup>[44]</sup> In fact, at Mercury, the Na D lines become moderately optically thick, with  $\tau$  of order 10.

<sup>[45]</sup> Taking Na as an example, the typical global average source rates are roughly  $\sim 5 \times 10^3$  and  $\sim 2 \times 10^6$  cm<sup>-2</sup> s<sup>-1</sup>, respectively.

As just noted, the decreased heliocentric distance of Mercury compared to the Moon induces much shorter surface residence times between bounces of atomic species on the surface, which may create a larger thermalized population of atoms at Mercury. Mercury’s smaller heliocentric distance (combined with its albedo) also causes its surface temperature to be much hotter (725 K, subsolar) than on the Moon (400 K, subsolar). This higher temperature causes more rapid outgassing of volatile or semivolatile constituents, increases the thermal scale height in the daytime atmosphere, and modifies the timescales required for both thermal accommodation and lateral transport. Owing to the strong dependence of outgassing rates on temperature, Mercury’s higher surface temperature may be a (or the) significant cause of the striking difference in Na/K ratios between the Moon and Mercury (see Table 4.3; notice there that the lunar and Mercurian values, though different, bracket the solar value).

Further still, Mercury’s elliptical orbit adds forcing functions on the input solar and particle flux, the compression of Mercury’s magnetosphere (see below), surface temperature. These factors, as well as Mercury’s cyclic heliocentric velocity variations create important variability in source strengths, photionization lifetimes, and radiation pressure forces on species.

The presence of a magnetic field at Mercury that is capable of standing off the solar wind most of the time (e.g., Hood and Schubert [1979]), and creating a magnetospheric cavity, cannot be underestimated when the lunar and Mercurian cases are compared. In addition to standing off the solar wind, and therefore reducing the effectivity of solar wind sputtering onto the surface, Mercury’s magnetic field acts to prevent direct ion loss to the solar wind, and establishes a magnetospheric reservoir of ions and electrons.<sup>[46]</sup> As such, the presence of an internal dynamo essentially eliminates the importance of the Manka and Michel [1971] solar wind loss mechanism (which is so important at the Moon) at Mercury, and instead causes photo-ions and charge exchange ions to be recycled to the surface, where they are later reneutralized. This is very likely a major cause of the more effective recycling of atmospheric species discussed above.

One might expect that a combination of magnetospheric processes, and the effects of Mercury’s elliptical orbit, would generate some significant time variability in Mercury’s atmosphere,<sup>[47]</sup> and this time variability has already been observed. A dramatic example of this kind of variability is the localized Na and K “emission cloud” enhancements observed at Mercury [Sprague et al., 1997 and Sprague et al., 1990, respectively]. These enhancements may be related to known changes in the direction of the interplanetary electric field relative to Mercury’s magnetosphere, which may cause large enhancements in the amount of recycled Na<sup>+</sup> brought to Mercury’s surface [Sprague, 1992; Hunten and Sprague, 1997].

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<sup>[46]</sup> Mercury’s magnetosphere is also a potential generator of polar auroral phenomena.

<sup>[47]</sup> The planet’s 3:2 spin:orbit coupling might also be expected to play a role.

Ion neutralization on impact, and either immediate return to the atmosphere as neutrals, or storage in localized cold spots to be released upon heating, may be responsible for some or all of the localized, short-lived Na bright spots seen in recent imaging experiments [Potter and Morgan, 1990, 1997]. More observations are needed to improve knowledge about the variability of Mercury's atmosphere.

In concluding this discussion, one must admit the obvious: The ways in which the various differences between the Mercurian and the lunar cases affect the distribution, sources, sinks, and recycling of Mercury's atmosphere are complex, and far from satisfactorily understood. However, the literature contains some important papers that may lead to a deeper understanding. I refer the reader to Goldstein et al. [1981] concerning H and He; Ip [1993] and Smyth and Marconi [1995b] on radiation acceleration; Potter and Morgan [1990] and Sprague [1993] on magnetospheric recycling of Na; Sprague [1990] and Killen and Morgan [1993] for the suggested crustal diffusion source; and Killen and Morgan [1993] and Smyth and Marconi [1995b] for general models of the combined effects of several mechanisms.

Looking toward the future, one is hopeful that either NASA or the European Space Agency (ESA) will stage a mission to follow up on the initial explorations of Mariner 10 some 25+ years ago.

## 5.0 SPECIAL TOPICS

In this final section before closing, I briefly touch on two little-studied but interesting topics regarding the lunar atmosphere: the impact of human exploration on the native lunar atmosphere, and the likely content and history of the lunar atmosphere over the past 4.6 Gyr, including impact-driven transients which have probably increased its bulk by orders of magnitude for short periods. I begin with a review of the literature available on human impacts.

### 5.1 Past and Potential Future Human Impacts on the Lunar Atmosphere

The rate of supply of gases to the native lunar atmosphere is of order  $10 \text{ g s}^{-1}$ , and the total mass of the atmosphere is only  $\sim 10^7 \text{ g}$ . Because this atmosphere has so little mass, it is particularly susceptible to human influence. This was dramatically demonstrated by the simple fact that each Apollo lunar landing mission deposited rocket exhaust and spacecraft effluents totaling  $\sim 0.2$  lunar atmosphere masses [Vondrak, 1974, 1988]. Of course, this gas was lost to space on a few ionization timescales, but the effects of repeated landings in the period 1969–1972 severely hampered ALSEP measurements (see §1) of the

lunar atmosphere.<sup>[48]</sup>

Any future, intensive lunar exploration phase using rocket-based technologies and other currently foreseen technologies<sup>[49]</sup> would involve substantial gas injection to the lunar atmosphere, severely perturbing its native state. Additionally, if the average injection rate were to exceed  $\sim 1 \text{ kg s}^{-1}$ , it would affect the pristine environment's suitability for some kinds of astronomical observations (Burns et al., [1988; Fernini et al., [1990]).

At present, the lunar atmosphere is optically thin to the photons and charged particles which drive the naturally cleansing loss processes, and its escape time is short. As a result, the whole ensemble of gas molecules on the dayside are subject to photoionization loss. This is why the effects of each Apollo landing were seen to dissipate over timescales of a few lunations.

Vondrak's work [1974, 1988], however, has shown that it would not be difficult to transform this situation into a different one. Making simple calculations about an increasingly dense, idealized (i.e., oxygen) lunar atmosphere, Vondrak found that as the number density of the lunar atmosphere increases, the exobase eventually rises above the surface, in effect shielding the atmosphere below it from escape, and thereby dramatically lengthening the time required for it to recover to the native state. More specifically, as shown in Figure 5.1, Vondrak found that for source injection rates  $\gtrsim 6 \times 10^4 \text{ g s}^{-1}$  (corresponding to a total atmospheric mass  $> 10^{11} \text{ g}$ , roughly  $10^4$  the present mass), the atmosphere switches from being photoionization loss dominated to being thermal escape [Jeans, 1923] dominated, with a consequent increase in characteristic escape time from tens of days to hundreds of years.

These considerations emphasize how fragile the native lunar environment is, and how easily human activities, even in the name of science, can affect this ancient wilderness.

## 5.2 The Primordial Lunar Atmosphere and More Recent Transients

Today the lunar atmosphere is a rarefied SBE, but simple considerations demonstrate that it was not always so thin. Cast into its simplest form, one finds three major epochs in the history of the lunar atmosphere; these are illustrated in Figure 5.2. During Epoch I, the Moon's surface was still hot from formation and displayed widespread exposed surface magmas. The atmosphere during this period, prior to final crustal formation, was a thick,

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<sup>[48]</sup> R.R. Hodges (pers. comm.) notes that Apollo remnants, including batteries, unspent seismic mortars, LM descent stages, and space suit backpacks may still be capable of contaminating the lunar atmosphere.

<sup>[49]</sup> Not to mention the mining activities envisioned by some.

thermally supported rock vapor pressure atmosphere. During Epoch II, which spanned the period from the end of the last magma ocean and the formation of the lunar crust  $\sim 4.4$  Gyr ago, until the tailoff of large impacts  $\sim 3.4$ – $3.0$  Gyr ago, the lunar atmosphere stochastically fluctuated between an SBE state and thicker environments owing to the effects of vulcanism and impacts. During the present epoch, Epoch III, the lunar atmosphere should be correctly called a time-averaged SBE (as should other SBEs) in which the rarefied SBE state is occasionally exceeded, owing to occasional impacts or internal outgassing events.

I now briefly sketch a few interesting details concerning the thicker atmospheres that have existed during Epochs I–III, with the hope that they will spur further research into this natal but fascinating subject area. I will discuss each of the three atmospheric epochs in turn.

*Epoch I: The Thick Primordial Lunar Atmosphere.* Geochemical evidence from lunar samples shows that accretional heating induced an early lunar epoch initially exhibiting either widespread or global magma oceans. Such surface magmas, with characteristic temperatures of 1000–2500 K, must have acted as sources of rock vapor, consisting primarily of silicon, aluminum, magnesium, sulfur, and iron oxides. Volatiles, including  $\text{H}_2\text{S}$ , may also have been outgassed. As a purely illustrative example, consider the magnitude and characteristics of a purely silicate oxide vapor envelope around the Moon. At a canonical magma temperature of 1500 K, the saturation vapor pressure of  $\text{SiO}_4$  is 100 bars— under these conditions the lunar atmosphere would be about as thick as Venus’s present atmosphere! The scale height of this atmosphere would be of order 75 km; the radiative output of the hot Moon under these conditions would be  $\sim 10^{26} (T/1500 \text{ K})^4 \text{ erg s}^{-1}$ .

One would expect this atmosphere to have displayed complex chemical and dynamical processes, which would have been affected by the ancient Moon’s closer position to the Earth, and the ancient Sun’s lower bolometric but higher UV luminosity (e.g., Kasting and Grinspoon [1991]).

Because the dimensionless escape parameter,  $\lambda$  (i.e., the ratio of gravitational to thermal energies), of the massive Epoch I lunar atmosphere would have been  $\sim 20$ , escape would not have been hydrodynamic, but would instead have been dominated by the standard Jeans process and scavenging by solar wind and solar UV (unless the atmosphere was hot, e.g.,  $T > 2000$  K; see Vondrak [1988]). Because the Moon was much closer to the Earth at early times, escape dynamics were faster, and more complicated, than they would be at the Moon’s present distance.

Throughout this epoch, the massive lunar atmosphere would have shielded the underlying “surface” from many impacts (though not from the infalling mass deposition itself), and may (particularly in its waning days) have created geochemical or geophysical evidence of its presence.

*Epoch II: The Era of Thick-Atmosphere Transients.* Subsequent to the era of a sustained, thick lunar atmosphere, there must have been an era during which vulcanism and occasional (e.g., large crater- or basin-forming) impacts either punctured the thin crust overlying subsurface magmas, or which themselves created regional-scale magma lakes. Lunar geochronology suggests that this era persisted until 3.8–3.4 Gyr ago. Sample dating of basalts (see Taylor [1982]) provides ample radiometric evidence that mare basalts, and therefore mare vulcanism, persisted until  $\sim 3.1$  Gyr ago. From this one concludes that throughout the period from  $\sim 4.4$  Gyr ago when the crust solidified until  $\sim 3.1$  Gyr ago when vulcanism effectively terminated, the Moon had a thin, volcanically supported atmosphere which was punctuated by brief and increasingly rare transients to high-mass states created by the dramatic but declining effects of large impacts.

A crude (and perhaps grossly inaccurate) scale for the “background” mass of this atmosphere would be the expected output from a single significant volcano, which might produce a steady-state atmosphere of order  $10^{14}$  g and a pressure of order  $10^{-8}$  bars; such an envelope would display a column mass of  $3 \times 10^{-4}$  g cm $^{-2}$ , a number density of order  $10^{11}$ – $10^{12}$  cm $^{-3}$  and a pressure of several to many tens of nanobars. This atmosphere would not be an SBE, but rather a conventional (though quite thin) collisional atmosphere. Vondrak’s [1974] calculations indicate an escape rate of order  $10^4$  g s $^{-1}$ , which gives a crude loss timescale (in the absence of replenishment) of a few years to a few tens of years. This fascinating ancient environment, including the attributes and possible signatures of the punctuated intrusions of more massive atmospheric transients owing to impacts during Epoch II, deserves further study.

*Epoch III: Transients from the Modern Lunar Atmosphere.* The boundary between Epochs II and III might be crudely defined as occurring when the lunar atmosphere first became an SBE for a timescale comparable to the timescale between major impacts. Based purely on the lunar cratering chronology established from Apollo era data, this transition probably occurred of order 3 Gyr ago. Since then, the lunar atmosphere has probably appeared, on average, much as it does today, but with brief, occasional transients to higher mass states occurring when significant impacts or rare, significant internal gas releases take place.

How often do such transient excursions occur? I consider here only impact-generated transients, and discuss two interesting cases. Case 1 is that the lunar atmosphere increases by an order of magnitude in mass to  $\sim 10^8$  g; though a dramatic increase, the atmosphere would remain an SBE. Case 2 is defined to be an impact that would transition the atmosphere out of the SBE regime, which requires a minimum total atmospheric mass of order  $10^{10}$  g.

For impacts onto rock at speeds of order 7–25 km s $^{-1}$ , as would be produced by objects in the Earth orbit crossing population, models predict the formation of 1–5 times the mass of



the impactor in vapor [Gault 1973; Haff et al., 1983], with characteristic gas temperatures of 2000–5000 K. The escape speed from the Moon ( $2.38 \text{ km s}^{-1}$ ) equates to a gas thermal temperature of  $\approx 16,000 \text{ K}$ , which little of the vapor would reach (O’Keefe and Ahrens [1982]; Morgan and Shemansky [1991]). Because of this, and because ionization effects do not become important at vapor temperatures below 20,000 K, essentially all of the vaporized mass remains as a neutral gas and is initially retained.

Impactors of scale  $3 \times 10^8$  and  $3 \times 10^{10} \text{ g}$  are required to induce cases 1 and 2, respectively.<sup>[50]</sup> For impactor densities of  $3 \text{ g cm}^{-3}$  the impactor radii corresponding to these masses would be only  $\approx 2$  and  $\approx 10$  meters, respectively. What is the frequency of such impacts? Recent calculations of the Earth-crossing impactor population and lunar impact rates (e.g., Bottke et al., [1994]; Rabinowitz et al. [1994]) differ by factors of a few, but indicate that the predicted mean times between impacts on the Moon by 2 m and 10 m projectiles are of order 5–10 years, and 100–200 years, respectively. By comparison, a comet impact is estimated to occur every  $\sim 10^7$  years [Shoemaker, 1983] and to generate  $10^{16.6-17.5} \text{ g}$  of vapor, corresponding to a microbar-class atmosphere; a Tycho-generating impactor occurs of order every  $\sim 10^8$  years and generates an atmospheric mass of order  $10^{19.5-20.5} \text{ g}$ , which would generate a millibar-class transient atmosphere.

The 100 year to 200 year timescale between impactors of sufficient mass to temporarily transition the lunar atmosphere out of the SBE state is particularly interesting. Vondrak’s escape rate calculations indicate that transient atmospheres with masses of  $10^{10} \text{ g}$  would decline in a few days back below the SBE boundary (owing to the development of an optically thick envelope and higher exospheric temperatures).<sup>[51]</sup> Such an atmosphere would then further decline to the ambient (i.e., present) quasi-static environment in a few years.<sup>[52]</sup> Crudely speaking, this implies that the duty cycle for significant lunar atmospheric transients above the current environment is of order 0.1–3%, which is surely nontrivial.

The fact that the modern lunar atmosphere routinely exhibits transients of this magnitude, and in fact briefly exits the SBE regime of order every 100–200 years, is not generally recognized. This, like the more severe departures of the lunar atmosphere from its present environment that occurred early in lunar history, deserves more rigorous investigation.

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<sup>[50]</sup> Cometary impacts at characteristic speeds of  $30\text{--}50 \text{ km s}^{-1}$  would import several times more energy per gram and require proportionately smaller impactors.

<sup>[51]</sup> Case 1 increases to an atmospheric mass of  $10^8 \text{ g}$  would be lost on timescales of a few months.

<sup>[52]</sup> A comet impact event atmosphere would likely take of order  $10^3$  years to decline back to the SBE boundary; a Tycho-forming event atmosphere would likely take of order  $10^6$  years to decline back to the SBE boundary.

## 6.0 OUTLOOK

The lunar atmosphere is tenuous indeed: Upper limits derived by Apollo-based instruments indicate that the entire native envelope weighs only  $\sim 100$  tons. However, the complexity and scientific value of this atmosphere are not commensurate with its low mass.

Tenuous as it may be, the lunar atmosphere contains vital information about the location of near-surface volatiles, including water, acts as a reservoir of gases released from the interior, and may even mirror the composition of certain surface-lying mineralogical units. Furthermore, as described in §4, the lunar atmosphere is the most accessible of the solar system's SBEs, and offers a rich variety of physical processes to study as analogs to other SBEs across the solar system. An important advantage of the Moon for such studies is that, we enjoy abundant surface samples and orbital geochemical data that provide key “boundary conditions” to the physics and chemistry at work, unlike any other similarly exposed planetary surface.

As one example, consider surface sputtering. Because the atmosphere is an SBE, chemical reactions between lunar atmospheric species and the lunar surface serve to modify the atmospheric composition and to control the transport physics of mobile species. Because sputtering (along with micrometeorite impacts) acts as a major source of neutral gases and ions, studies of the lunar atmosphere offer to improve knowledge about the rate and kind of weathering processes that affect uppermost planetary regolith. Such weathering is driven by the constant rain of charged particle and photon radiations from the Sun; radiation is known to modify the color, albedo, and microphysical structure of planetary surfaces (e.g., Johnson [1990]). These data provide potentially important information which, when coupled to atmospheric measurements, allow direct solution for weathering yields as a function of surface composition, temperature, and microphysical roughness. Once accurately established, lunar surface weathering rates can then be used to translate atmospheric abundances on other planets and satellites into surface elemental compositions.

Despite such motivations and the great progress made in recent years concerning the nature and attributes of the lunar atmosphere, one remains fundamentally ignorant of the basic processes at work there. The first-order questions that remain to be resolved include:

- What is the full composition of the lunar atmosphere?
- Why are so many expected neutral atomic species, like H, C, N, O, and Mg, missing?
- What are the dominant source and sink mechanisms for the major species?
- How does the composition and structure vary spatially and temporally?

- Do internal gas release events correlate with certain surface features?

These issues can only be resolved by obtaining more and better data of several kinds.

With regard to groundbased efforts, it would be particularly useful to obtain more sensitive upper limits on additional species in the lunar atmosphere, and to obtain temporally dense Na and K data sets spanning a full lunation. A concerted effort using modern detectors and large-database management techniques to search for, and determine the occurrence frequency, of LTP would also be highly productive.

Additional insights into the composition of the lunar atmosphere are likely to be obtained by spectroscopic studies using HST, and the upcoming Far Ultraviolet Spectroscopic Explorer (FUSE) and Chandra x-ray missions as well.

However, the most valuable experiments that can be envisioned next will involve placing a suite of optical and mass spectrometers in lunar orbit (or even on the surface) aboard a clean, robotic spacecraft. Such a mission could easily be accomplished in the next few years.<sup>[53]</sup>

In the more distant future, one envisions an even more ambitious prospect: The active perturbation of the lunar atmosphere as a tool for studying the response of SBEs to specific stimuli. Such experiments, for example involving temporary compositional and density modifications, are possible only as a result of the lunar atmosphere's low mass, and would open an exciting new era of laboratory-style atmospheric studies on a planetary scale.

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<sup>[53]</sup> And clearly must be accomplished before the native environment is overwhelmed by extensive exploration expected when humans return.

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## Figure Captions

1.1. On the lunar ionosphere. Upper panel: Schematic representation of the sources of electric fields near the northern hemisphere of the Moon. The interplanetary field arises due to the motion of the solar wind magnetic field; the lunar surface field arises from surface charges. The terminator is the shaded area, labeled with SR=sunrise, and SS=sunset. Bottom panel: Schematic from SIDE data representing the variation in photoelectrons and lunar atmospheric ions with altitude. Adapted from Vondrak [1988].

1.2. LACE argon data measured at the Apollo 17 ALSEP site in the lunar northern hemisphere from December 1972 through September 1973; SR=sunrise, SS=sunset. The dashed lines represent model fits for the daytime atmosphere, which LACE could not measure owing to saturation effects (see text). Adapted from Hodges [1975].

1.3. Apollo 17 LACE helium data. The data (with  $1\sigma$  error bars shown) show the average diurnal variation in lunar He over the 10 lunations LACE operated; the (solid line) model fit is a model distribution for a solar wind source of  $1.35 \times 10^7 \text{ cm}^{-2} \text{ s}^{-1}$ . Adapted from Hodges [1975].

1.4. Top panel: Schematic representing the  $^{238}\text{U}$  decay chain that results in the production of  $^{222}\text{Rn}$  and later,  $^{210}\text{Po}$ . Middle panel: The distribution of  $^{222}\text{Rn}$  counts over the whole Moon during Apollo 15, showing the distinct deviation of the Aristarchus region (at right), compared to a simple gaussian model; here GET is ground elapsed time since launch, which is measured in hours. Lower panel: Apollo 15 orbital  $^{210}\text{Po}$  count rates measured over the lunar surface as a function of lunar longitude; data from all latitudes overflown (35 deg south to 35 deg north) have been coadded to show only the longitudinal dependence. Adapted from Gorenstein et al. [1974].

1.5. Sketches drawn by Apollo 17 astronaut E. Cernan of a sunrise, drawn in lunar orbit; the times in minutes and seconds refer to the time (e.g., T minus 6 min) before sunrise. Adapted from McCoy and Criswell [1976].

1.6. Reduced Potter and Morgan [1988b] spectrum of the lunar sodium D lines, measured 600 km above the equatorial bright limb. The units on the ordinate are counts from the spectrometer Potter and Morgan used.

1.7. Sodium 5890 Å D<sub>2</sub>-line intensity above the subsolar limb, comparing a fit with both cool and hot thermal components (solid line) to the fit attained if only a thermal component with a 120 km scale height were present (dotted line). Adapted from Potter and Morgan [1988b].

1.8. Potter and Morgan's [1997] demonstration that the Na column density varies with

latitude (and thus solar zenith angle) like  $\cos^2(\chi)$ , where  $\chi$  is the solar zenith angle.

1.9 The extended atmosphere of the Moon as portrayed in sodium ( $D_1+D_2$ ) brightness under conditions of quarter- and full-Moon phases [Mendillo et al., 1997b].

1.10 The relative brightness variation with altitude from four sodium images. The latitudes of the four image sites (all northern hemisphere) are shown. Each image was corrected for vignetting, bias, gain, and scattered light. Plotted with each cut is the best two-temperature fit. In panel (a),  $3\sigma$  lower limits for each temperature are given, where  $\sigma$  is the random error in the data. In panels (b)-(d), the  $3\sigma$  uncertainties in each temperature are given in parentheses. Each temperature component is shown individually along with the combined fit. The percentages for each temperature refer to the fractional abundances at the surface. Adapted from Stern and Flynn [1995].

1.11 Line-of-sight column abundances at 40 km above the limb for Si, Al, Ca, Fe, Ti, and Li relative to Na from both the stoichiometric model (filled circles) and the observations (triangles). The detected value for K is within a factor of 2 of the predicted stoichiometric value. Bottom: Ratios of observed upper limit column abundances to predicted values. A ratio of unity indicates stoichiometric behavior relative to Na. Arrows denote that values are upper limits in the cases of Si, Al, Ca, Fe, Ti, and Li. Note that the K value is within a factor of 2 of unity.

1.12 Mass-to-charge ( $m/q$ ) spectra from the AMPTE SULEICA instrument showing the detection of lunar ions when it was downstream of the Moon. Adapted from Hilchenbach et al. [1991].

2.1. Upper panel: The dynamics of transport in the lunar atmosphere. Bottom panel: The interchange of gases between reservoirs, sources, and sinks. Adapted from Smyth and Marconi [1995a].

2.2. Model results showing the variation in solar radiation pressure on Na atoms as a function of time in 1993, showing both the effect of the monthly lunar orbit, and longer-term annual variations driven by the Earth's orbit. Upper panel: For Na atoms initially moving toward the Sun at  $1 \text{ km s}^{-1}$ . Bottom panel: for Na atoms initially moving away from the Sun at  $1 \text{ km s}^{-1}$ . Adapted from Smyth and Marconi [1995a].

2.3. Comparison of the spatial character of the lunar Na and K atmospheres at first and last quarters. Upper panel: Sodium. Lower panel: Potassium. These particular calculations were run for surface atom ejection speeds of  $2.0 \text{ km s}^{-1}$ ; 259 atoms were used in this Monte Carlo simulation, the position of each being shown every 900 seconds. The lunar velocities at first and last quarters are  $-1.5 \text{ km s}^{-1}$  and  $+1.5 \text{ km s}^{-1}$ , respectively. The distance to the Earth and the scale of the Earth are not to scale relative to the Moon and the lunar

atmosphere, which are, however, to scale with one another. Adapted from Smyth and Marconi [1995a].

3.1. Illustration of the competing source mechanism concept. adapted Adapted from Sprague et al. [1992].

5.1. Loss rates for a 16 amu lunar atmosphere (model) as a function of atmospheric mass. Adapted from Vondrak [1974].

5.2. Schematic illustrating the three epochs of the lunar atmosphere.

**Table 1.1**  
**Native Lunar Atmospheric Species: Abundances**

Species	Detection Method	Number Density (cm <sup>-3</sup> )	Reference
He	LACE Mass Spectroscopy	2×10 <sup>3</sup> , 4×10 <sup>4</sup> (day, night)	Hoffman et al. [1973]
Ar	LACE Mass Spectroscopy	1×10 <sup>5</sup> , 4×10 <sup>4</sup> (day, night)	Hoffman et al. [1973]
Rn	Alpha Particle Spectroscopy	variable	Gorenstein et al. [1973]
CH <sub>4</sub>	LACE Mass Spectroscopy	1×10 <sup>4</sup> (pre-sunrise)	Hoffman & Hodges [1975]
N <sub>2</sub>	LACE Mass Spectroscopy	8×10 <sup>2</sup> (pre-sunrise)	Hoffman & Hodges [1975]
CO	LACE Mass Spectroscopy	1×10 <sup>3</sup> (pre-sunrise)	Hoffman & Hodges [1975]
CO <sub>2</sub>	LACE Mass Spectroscopy	1×10 <sup>3</sup> (pre-sunrise)	Hoffman & Hodges [1975]
Na	Groundbased Spectroscopy (5890 Å)	070	Potter & Morgan [1988a]
K	Groundbased Spectroscopy (7699 Å)	017	Potter & Morgan [1988a]
H	Apollo 17 UV Spectroscopy (1216 Å)	<017 (3σ)	Feldman & Morrison [1991]
O	Apollo 17 UV Spectroscopy (1304 Å)	<500 (3σ)	Feldman & Morrison [1991]
N	Apollo 17 UV Spectroscopy (1200 Å)	<600 (2σ)	Fastie et al. [1973]
C	Apollo 17 UV Spectroscopy (1657 Å)	<200 (3σ)	Feldman & Morrison [1991]
S	Apollo 17 UV Spectroscopy (1474 Å)	<150 (3σ)	Feldman & Morrison [1991]
Kr	Apollo 17 UV Spectroscopy (1236 Å)	<20000 (2σ)	Fastie et al. [1973]
Xe	Apollo 17 UV Spectroscopy (1470 Å)	<3000 (3σ)	Feldman & Morrison [1991]
H <sub>2</sub>	Apollo 17 UV Spectroscopy (1462 Å)	<9000 (3σ)	Feldman & Morrison [1991]
CO	Apollo 17 UV Spectroscopy (1510 Å)	<14,000 (3σ)	Feldman & Morrison [1991]
Si	Groundbased Spectroscopy (3906 Å)	<048 (5σ)	Flynn & Stern [1996]
Al	Groundbased Spectroscopy (3962 Å)	<055 (5σ)	Flynn & Stern [1996]
Ca	Groundbased Spectroscopy (4227 Å)	<001 (5σ)	Flynn & Stern [1996]
Fe	Groundbased Spectroscopy (3859 Å)	<380 (5σ)	Flynn & Stern [1996]
Ti	Groundbased Spectroscopy (5036 Å)	<001 (5σ)	Flynn & Stern [1996]
Ba	Groundbased Spectroscopy (5536 Å)	<0.2 (5σ)	Flynn & Stern [1996]
Li	Groundbased Spectroscopy (6708 Å)	<0.01 (5σ)	Flynn & Stern [1996]
Al	HST UV Spectroscopy (3092 Å)	<11000 (5σ)	Stern et al. [1997]
Mg	HST UV Spectroscopy (2852 Å)	<6000 (5σ)	Stern et al. [1997]
OH	HST UV Spectroscopy (3085 Å)	<10 <sup>6</sup> (5σ)	Stern et al. [1997]

Notes: (1) In cases where upper limits are given on number density, only the best existing upper limit is quoted on a given species, with appropriate confidence level in  $\sigma$ . (2) All species number densities are quoted as dayside values unless otherwise noted. (3) Daytime contaminants detected by Apollo instruments not included. (4) Number densities for Feldman and Morrison [1991], Flynn and Stern [1996], Stern et al. [1997] all adjusted to

an exospheric temperature of  $T=400$  K.

**Table 3.1**  
**Characteristic Loss Timescales in the Lunar Atmosphere**

Species	Thermogravitational (390 K)	Thermogravitational (1000 K)	Photoionization	e <sup>-</sup> Impact
He	0.2 d	0.04 d	162 d	2900 d
Ar	500 Myr	03 yr	025 d	0550 d
Na	011 Kyr	23 d	0.6 d	0015 d
K	011 Gyr	16 yr	0.4 d	0010 d
H <sub>2</sub> O	175 yr	06 d	029 d	0165 d

Notes: (1) Ionization loss timescales are in the presence of their respective sources and ignore shadowed time. (2) Despite not being discovered, water is included for reference; the dominant loss timescale for H<sub>2</sub>O in the lunar atmosphere is its 1.2-day photodissociation timescale. (3) Rn is not listed, because the excess energy of emission is greater than the lunar escape speed; escape is instantaneous.

**Table 3.2****Surface Residence Times and Solar Zenith Angles for Lunar Sodium**

T (K)	$t_r$ (sec)	Solar Zenith Angle (deg)
300	$3 \times 10^5$	80
400	7	00
500	0.01	N/A

**Table 3.3**  
**Lunar Gas Reservoirs, Sources, and Sinks**

Species	Reservoir	Primary Source(s)	Primary Sink
He	Solar Wind, Lunar Interior	Thermal Desorption and Sputtering	Jeans Escape
Ar	Lunar Interior	Thermal Desorption	Photoionization
Rn	Lunar Interior	Outgassing	Decay Half-life
Po	Lunar Interior	Outgassing	Photoionization
Na, K	Lunar Regolith, Meteorites/Comets, Solar Wind	Sputtering and Thermal Desorption	Photoionization



**Table 4.1**  
**Detected Surface Boundary Exospheres: Some Relevant Attributes**

Object	Species Detected	Gravity ( $\text{cm s}^{-2}$ )	Dipole <b>B</b> (nT)	Total Detected Surface Number Density ( $\text{cm}^{-3}$ )
Mercury	He, Na, K	372	$\sim 330$	$8 \times 10^4$ (day)
Moon	He, Ar, Rn, Po, Na, K	163	$< 0.2$	$2 \times 10^5$ (night)
Io	SO <sub>2</sub> , SO, S, O, Na, K	187	$\sim 1500$	$10^{13}$ (max)
Europa	O, Na	281	$< 240$	$2 \times 10^4$
Callisto	H	121	??	$2 \times 10^4$

**Table 4.2**  
**Daytime Atmospheric Constituents: The Moon and Mercury**

Species	Mercury ( $\text{cm}^{-3}$ )	Moon ( $\text{cm}^{-3}$ )
H	200	<17
He	$6 \times 10^3$	2000–40,000
O	$\leq 4 \times 10^4$	<500
Na	$2 \times 10^4$	70
K	500	17
Ar	$< 3 \times 10^7$	$4 \times 10^4$
Total	$5 \times 10^4$	$8 \times 10^4$

Notes: (1) Abundances are average daytime abundances. (2) Abundances for H, He, O, and Ar at Mercury are from Broadfoot et al. [1976], for Na, K at Mercury are from Potter and Morgan [1985, 1986] and Sprague et al. [1990, 1997]. (3) Abundances for H, He, O, and Ar for the Moon are from Hodges et al. [1973], for Na and K at the Moon see Potter and Morgan [1988a]. (4) Adapted with permission from Hunten and Sprague [1997].

**Table 4.3**  
**Comparative Mercurian and Lunar Sodium and Potassium Abundance Ratios**

Species	Sun ( $\text{cm}^{-3}$ )	Mercury ( $\text{cm}^{-3}$ )	Moon ( $\text{cm}^{-3}$ )	Mercury/Moon Ratio
Na	$6 \times 10^4$	$4 \times 10^4$	70	$\sim 600$
K	$4 \times 10^3$	500	17	$\sim 030$
Na/K Ratio	14	$\sim 80$	$\sim 4$	20:1

Note: Solar system abundances are per  $10^6$  Si atoms. This table is adapted from Hunten and Sprague [1997].