THE IMPACT OF HUMAN PRESENCE AND HUMAN ACTIVITIES ON THE TOTAL MASS AND CHEMICAL COMPOSITION OF THE VERY THIN LUNAR ATMOSPHERE

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Abstract

In the last fifty years, we have witnessed the impact of human activity on the Earth. Unprecedented changes in the Earth's atmosphere have undeniably been caused by human presence. As early as 2025, for the first time, NASA will send humans to another planetary body for long-term habitation. It is calculated, that the emissions of each Apollo mission, in less than 24 hours of human presence on the surface, caused the lunar atmosphere to double(Vondrak). The Artemis program's goal to inhabit the Moon will undoubtedly catalyze inadvertent changes to its surface and atmosphere to many times the scale of Apollo. To prevent mistakes we have made on Earth we must measure and model our impact on the lunar atmosphere from the onset of human presence for prolonged times. This paper will describe the lunar equilibrium, qualify the prior human impact, present future sources of perturbation to the atmosphere via the Artemis missions, and suggest a quantitative model of the perturbed exosphere. This research will allow us to have a better understanding of the lunar atmosphere equilibrium, predict our long-term impact on the lunar atmosphere, and lay the foundation for understanding our impact on other planetary bodies, like the Moon.

Motivation

At first, it may seem like our initial impact on the Moon will be negligible. After all, it took hundreds of years and billions of people to cause the impact we have on Earth today. However, the Moon's atmosphere is significantly less massive and subject to change. It is so thin that the ascent, descent, and human activities of each Apollo mission caused the density of its atmosphere to double (Vondrak, 1974, 1988, Levine and Zawodny, 2007). According to mass spectrometers left on the moon, effects of this perturbation were felt by the lunar atmosphere for the following three to four months(Vondrak). This data collected from the mass spectrometers left by Apollo 12 and 14 clearly show human presence on the moon will cause a significant change in the lunar atmosphere. Before we build a long-term settlement we need to understand the original composition of the lunar atmosphere and how mankind will perturb it.

Not only do we need to have this record of our impact on another planetary body for ethical concerns, but also for the sake of future exploration. NASA plans to send humans to the moons of Jupiter and Saturn which are similar to the Moon. Undoubtedly, we will look at the success of the Artemis missions as a guide for future exploration. We need to have an understanding of how we impacted our lunar atmosphere to predict how we will affect other planetary bodies.

Lastly, and most importantly, the safety of our astronauts on the Moon may be at risk. The increase in the lunar atmosphere's density will also impact lunar dust. Lunar dust has properties similar to particlized glass and thinly coats the lunar regolith (Heiken, Vaniman and French, 1991). Along with it being reported to damage equipment, such as spacesuits, it also made its way into the lunar module and caused reported psychological and physical problems. Apollo 17 astronaut, Captain Gene Cernan said, "I think dust is probably one of our greatest inhibitors to a nominal operation on the Moon. I think we can overcome other physiological or physical or mechanical problems except dust" (Heiken, Vaniman and French, 1991). The Apollo astronauts only spent a few hours on the Moon, for the Artemis astronauts who will spend significantly longer on the moon, this pervasive dust will be a problem. It is absolutely necessary, regardless of the leakage of the lunar atmosphere, for the safety of our astronauts that we model our impact on lunar dusts primary mode of transportation. This paper aims to present the unperturbed equilibrium and suggest a predictive model on the behavior of the lunar atmosphere.

The Modern Atmosphere

The Moon was formed when a mars sized object collided with the Earth. It is subsequently postulated, its primordial atmosphere was composed of similar components to that of the Earth's early atmosphere such as water vapor, carbon dioxide, and ammonia. However, these molecules are not present in the modern lunar atmosphere and are expected to have leaked into space due to the Moon's low gravity. The present-day atmosphere is believed to be an equilibrium between the natural sources and sinks of gasses on the moon(Debra 2017).

Due to the low gravity of the Moon, the current lunar atmosphere is extremely thin. It has a mass of 10^7 grams, a total density of 10^6 particles per cm^3, and total pressure of only 3×10^{-15} bar. This is classified as a surface boundary exosphere(Lunarpedia). Essentially, the mean free path, a distance until a collision with another particle, is larger than the effective pull of the moon's gravity. This means any particle accelerated past the lunar escape velocity of 2.38 km/s is almost guaranteed to escape(UC Davis).

Table 1: A complete list of the composition and abundances of the lunar atmosphere

Gas	Particle Density
Helium 4 (4He)	40,000 particles/ cm^{-3}
Neon 20 (20Ne)	40,000 particles/ cm^{-3}
Hydrogen (H2)	35,000 particles/ cm^{-3}
Argon 40 (40Ar)	30,000 particles/ cm^{-3}
Neon 22 (22Ne)	5,000 particles/ cm^{-3}
Argon 36 (36Ar)	2,000 particles/ cm^{-3}
Methane	1,000 particles/ cm^{-3}
Ammonia	1,000 particles/ cm^{-3}
Carbon Dioxide (CO2)	1,000 particles/ cm^{-3}
Trace Oxygen (O^+)	trace
Aluminum (Al^+)	trace
Silicon (Si^+)	trace
Possible Phosphorus (P^+)	trace
Sodium (Na^+)	trace
Magnesium (Mg^+)	trace

(Lunarpedia)

The Natural Sources and Sinks

In order to completely understand the lunar atmosphere and how it will be affected by human presence we must understand the variable sources and sinks that are occurring on and near the surface that contribute to the atmosphere. In this section, I will step-by-step describe the various natural processes that cause sources and sinks of atmospheric elements.

Radioactive Decay

Radioactive decay is a process by which unstable isotopes disintegrate spontaneously, resulting in the release of particles and/or energy. On the Moon, uranium—238, thorium—232, and potassium—40 are the most significant isotopes for radioactive decay, and are present in the regolith at concentrations of approximately 16 ppm, 10 ppm, and 1.2 ppm, respectively. The decay of these isotopes produces various daughter products, which are released into the lunar atmosphere through radiogenic outgassing, contributing to the overall composition of the lunar atmosphere, especially with regard to helium—4 and argon—40(Crotts).

Volcanism

Volcanism is another important process that has historically impacted the lunar atmosphere. Volcanic activity is believed to have increased the lunar atmosphere to one hundredth of earths current mass. However, the Moon's volcanic activity was most prominent during the early stages of its history. Today there are signs of ongoing volcanic activity in the form of gas emissions from certain regions under the lunar surface, including sulfur dioxide, carbon dioxide, and water vapor, among other gases. But, currently volcanism not calculated to make large contributions to the lunar atmosphere(Debra).

Meteorites

Meteorite impacts can also have an effect on the lunar atmosphere. When a meteorite strikes the Moon, it can vaporize the surrounding regolith, releasing gases and particles into the exosphere.

One example of the impact of meteorites on the lunar atmosphere is the detection of sodium in the lunar exosphere. Sodium is not a major component of the Moon's surface, but it has been observed in the exosphere at concentrations of up to several thousand atoms per cubic centimeter. This sodium is thought to be released into the exosphere by meteorite impacts, where it is ionized by solar radiation and becomes visible as a glowing "sodium tail"(Trigo-Rodríguez).

Thermal Escape

Thermal escape is a process that thins the lunar exosphere by allowing gas molecules to escape to space due to their high kinetic energy. The gases that make up a majority of the lunar exosphere, such as hydrogen, helium, argon, and neon, have very low masses and are therefore easily lost to space through thermal escape. Studies of the lunar atmosphere have shown that the rate of thermal escape varies depending on the time of day and the season(Coates). During the lunar day, when the surface of the Moon is exposed to the sun, the temperature of the gas molecules increases to about 400 Kelvin and the rate of thermal escape is higher. During the lunar night temperatures are reduced to 140 Kelvin, and the rate of thermal escape decreases.

Thermal escape is the largest sink in magnitude in the lunar atmosphere. In a paper by Needham et. al the effect of thermal escape on a high mass lunar atmosphere was calculated. "such interactions and the consequent loss rate change significantly when gas is added to the atmosphere (e.g., through an eruption) at rates greater than 100 kg s^{+1}, and when the atmospheric mass exceeds 108 kg (Vondrak et al., 1974). Under those conditions, the atmosphere transitions to a conventional collisional atmosphere, with a higher loss rate on the order of 104 g s^{+1} (Stern, 1999). This higher loss rate is dominated by thermal escape"(Needham et. al). With the increase in lunar mass the mean free path that particles can take will be reduced. However, as is explained in the detail in the model section the rate of thermal escape is positively related to the amount of an individual particle in the atmosphere. As Vondrak calculates, the increase in atmosphere will cause to an increase in the rate of release due to thermal escape. Intuitively, it makes sense that the moon will desire an equilibrium as it is believed the current lunar atmosphere has been the same for the last millions of years.

Solar Wind

Solar wind is both a source and a sink of atmospheric lunar elements. Solar wind is a stream of charged particles (mostly protons and electrons) that flow outward from the Sun and interact with the Moon's atmosphere(Funsten).

The sink of particles is caused by collisions called sputtering. Particles are ejected from the Moon's surface due to high-energy particle impacts. These particles can be ejected through ion implantation, elastic collisions, and inelastic collisions. In addition to physical sputtering, particles can be lost due to chemical sputtering. This occurs when high-energy particles collide with surface atoms or molecules and cause chemical reactions that result in the ejection of atoms or molecules from the surface. It is important to note that because the lunar atmosphere is a surface boundary exosphere, physical sputtering events are rare. With an increase in mass, the rate of sputtering collisions would rise. Therefore causing an increase in the escape of these particles(Coates).

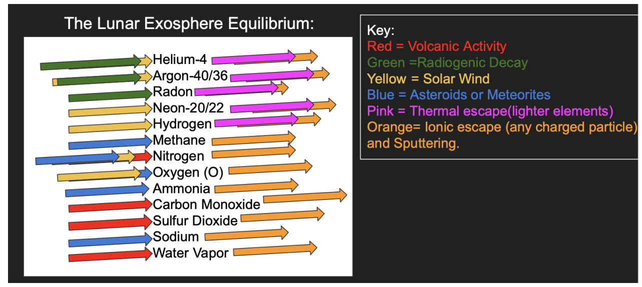

Figure 1: Source and Sink Visualization

In addition to colliding with atmospheric atoms, solar wind particles can become trapped in the lunar gravity and are thought to be the largest contributor to the lunar atmosphere. Solar wind collides with the surface of the moon and loses its energy due to the collision. This then traps it in the lunar exosphere. Solar wind is mainly comprised of H and HE molecules. As is calculated in table 4 the rate of escape of Helium, Neon, and Hydrogen molecules are the highest. However, as seen in 3 their abundances are also the highest. This means that they must be produced by a large source. In the case of Hydrogen and Helium that source is lunar wind. It is calculated that about 1kg of particles are delivered per minute(a very small fraction of these are retained)(Funsten).

(Source: The Author)

NASA's Impact

The Apollo Missions

While the Apollo missions were undoubtedly a massive success, the issues associated with doing something for the first time persisted. One such problem was associated with the readings of the cold cathode ion gauge. These readings were consistently driven off-scale by the ascending and descending Apollo missions. In fact, it is estimated that "each Apollo landing released as much gas(as is present in the unperturbed atmosphere) while on the moon" (Vondrak, 1974). Subsequently, over the six missions about six times as much gas was released into the lunar atmosphere as was initially present. This incredible result is only possible because of how thin the lunar exosphere is, 10^7 grams(Lunarpedia). However, it is indicative of the huge effect that humans can have on the moon's atmosphere.

Additionally, data collected proceeding Apollo 14s departure indicates that "a large amount (perhaps 10 percent) of the lunar module exhaust gas (a mixture of about 20 percent H2O with a wide variety of C-H-O-N species; Freeman et al., 1972) was adsorbed onto the lunar surface during the first lunar night after the astronauts departed, to be released rapidly as the sun rose again"(Spudis, P. D., and Taylor). While these gasses did eventually dissipate but took about three to four months to do so. This means that any mass spec or cold cathode measurements will be severely contaminated within 3-4 months of Artemis landing, if not longer(Vondrak 1974).

These effects, the doubling of the atmospheric mass and subsequent density, and pressure changes, for long periods of time, were induced by relatively short visits to the moon. The duration of the Apollo missions were as follows, Apollo 11: July 20-21, 1969 (21.5 hours on the lunar surface), Apollo 12: November 19-20, 1969 (31.5 hours on the lunar surface), Apollo 14: February 5-6, 1971 (33.5 hours on the lunar surface), Apollo 15: July 30-August 2, 1971 (66 hours on the lunar surface), Apollo 16: April 20-23, 1972 (71 hours on the lunar surface), and Apollo 17: December 11-14, 1972 (75 hours on the lunar surface). With more frequent visits to the moon, new activities, and the goal of a permanent stay, humankind will surely induce changes of greater magnitude that will last longer than 3-4 months(NASA 2021).

To exactly quantify the contribution to the lunar atmosphere due to the exhaust of the lunar module, I received an unpublished internal report from Northrop Grumman detailing the composition of their exhaust(Aronowitz). Northrop Grumman reports that there was 8348 kg of propellant used in the descent and ascent stages of the Lunar Module. This gas will produce exhaust in the ratios specified by figure . It is immediately obvious that an atmosphere with a mass of 10^7 grams will be severely impacted by a release of 8.348×10^7 grams of exhaust fuel. This does not take into account the leakage of oxygen from the lunar module, the biologically produced contaminants(see column 2 of table), the kick-off of lunar dust due to the lunar rover vehicle(unknown), or gasses released from the surface due to the landing and exploration process(unknown).

The rates of sources of lunar elements, total abundance measured on the moon, and human impact on these elements are visualized in table 3. This rate will be used in the proposed model(Aronowitz).

(Lunarpedia)

The Artemis Missions

The main goals of the Artemis missions are to, conduct scientific research and exploration of the moon, test new technologies and systems that will enable human exploration of Mars, establish a sustainable human presence on the moon, and to enable commercial and international partnerships in space(NASA 2021).

Table 2: Contribution to the lunar atmosphere from the lunar module engines and biological contamination

Gas	Kg per/mission	kg per/hour
Hydrogen (H2)	1053	1.3E-5
Methane	0	3.3E-5
Carbon Dioxide (CO2)	308	0
Oxygen (O^+)	24.1	0
H2S	0	2.8E-9
H20	3005	0
N_2	2671	0
C0	800	3.9E-6

Table 3: Lunar Atmosphere from Mass Spectrometer Readings

Component	**Initial Abundance** (cm^{-3})
Helium	40,000
Neon	45,000
Hydrogen	35,000
Argon	30,000
Methane	1,000
CO_2	1,000

Artemis I launched in November of 2022 and successfully demonstrated the unmanned capabilities of the new Lunar Module(LM). Artemis II will be a manned flight around the moon that will continue to test the deep space capabilities of the LM. Artemis III is expected to be launched in 2025 and will bring mankind back to the moon(NASA 2021).

In the context of the lunar atmosphere Artemis III is a large turning point. Currently, there are no plans to bring a mass spectrometer or cold cathode ion gauge to measure the impact of the Artemis missions on the lunar atmosphere. Astronauts will land near the south pole of the moon and stay for 6.5 days. During this time they will conduct multiple experiments that will determine the ability of long-term human presence on the moon. These activities include Lunar Rover Vehicle expeditions, geologic investigation on the lunar surface and the presence of water(mining), testing new technologies such as space suits and energy cells, and establishing a sustainable infrastructure on the moon(Sitirone).

With the time spent on the surface exceeding that of Apollo, it is expected that Artemis III will once again double the lunar atmosphere. However, unlike previous missions, we are planning on mining which will create additional leakages of gas, longer explorations that will kick up more dust, building a human habitat that will kick up large amounts of lunar dust, additional payload deliveries will also be continuously delivered to the moon and if all goes right frequent manned missions. With the danger of lunar dust and the previous perturbations of the lunar atmosphere, the lack of a mass spectrometer for these missions is surprising. With the behavior of lunar dust being directly linked to the charge and chemical composition of the lunar atmosphere, it is imperative that NASA understands the changing dynamics of the moon.

Unmanned Missions

Perhaps even more alarming than NASA's manned missions and potential mining of the lunar atmosphere is the series of robotic missions it has funded. "Through NASA's Commercial Lunar Payload Services (CLPS) initiative, 14 U.S. companies are on contract and eligible to bid on science and technology payload deliveries to the Moon. Astrobotic and Intuitive Machines each have one task order award for deliveries in 2021. Astrobotic will carry 11 payloads to Lacus Mortis, a larger crater on the near side of the Moon, and Intuitive Machines will carry five payloads to the Aristarchus Plateau, a volcanic terrain in Oceanus Procellarum that is one of the Moon's largest ore deposits (Hawke et al., 1990; Gaddis et al., 2003). Exploring the polar regions has been a high exploration priority for the past four decades. To that end, Masten Space Systems has been awarded one task order to deliver and operate eight payloads – with nine science and technology instruments to the lunar south polar region in 2022. In June 2020, NASA announced that Astrobotic would also deliver the agency's Volatiles Investigating Polar Exploration Rover (VIPER) to the south polar region in 2023"(NASA. (2020). Artemis III Science Definition Report). These 27 unmanned missions are just the beginning of our presence on the moon. However, there is no planned way of knowing their impact on the lunar atmosphere. Due to the smaller descent and no ascent engines, these missions will have significantly less contribution to the lunar atmosphere, but with a higher frequency and separate locations on the moon, they could cause a large increase in the lunar atmosphere.

Out of these 27 missions only one is attached with a mass spectrometer. This mission, The Polar Resources Ice Mining Experiment-1, or PRIME-1 will travel to the south pole before Artemis III and search for water(Vitug). One way this module measures what it is mining is through a mass spectrometer. This will have the additional effect of understanding the rate at which gasses will be released during the larger Artemis mining operations. While the presence of a mass spectrometer indicates a capability to measure gaseous output it is not directed towards the atmosphere and will provide no data on the human effect not caused through mining(Vitug). To understand Artemis's unique impact additional atmospheric measurement systems must to be funded.

A Proposed Model

The current state of the moon is an equilibrium. It is believed that the abundances of metabolites on the moon have been relatively constant aside from some sun spots and asteroid collisions(Debra). This means that the natural sources and natural sinks currently equal each other. In order to simplify my model I assume that the only natural sink to the lunar atmosphere is thermal escape also known as jeans escape. This is the largest sink in magnitude and can be calculated by the following equations.

$$\theta_{escape} = n(z)v_0/(2\sqrt{\pi})(v_{esc}^2/v_0^2 + 1)\exp{(v_{esc}^2/v_0^2)} \tag{1}$$

$$v_0 = \sqrt{(2kT)/m_{particle}} \tag{2}$$

$$v_{esc} = \sqrt{(2GM_{planet})/(R_{planet})} \tag{3}$$

(Coates) These equations are derived from the distribution of free gas. The energy of the system is related to the temperature and the rate of expected tunnelling to escape is calculated. The variables are as follows, θ_{escape} is the rate of escape in particles per meter squared per second, n(z) is the particle density in cm^-3, v_0 is the most probable velocity in km/s, v_{esc} is the escape velocity in km/s, $m_{particle}$ is the mass of the particle in kg, T is the average temperature of the atmosphere in Kelvin, G is the gravitational constant, k is Boltzmann's constant, and R_{planet} is the radius of the moon. I wrote these equations in python and calculated the following table.

Table 4: A complete list of the mass escape rates of individual particles in the lunar atmosphere

Gas	Mass	Escape rate (Pm^-2s^-1)
Helium (4He)	6.64E-27 kg	1.32E7 Pm^-2s^-1
Neon (20Ne)	3.36E-27 kg	2.089E7 Pm^-2s^-1
Hydrogen (40/36Ar)	31.67E-27 kg	5.292E6 Pm^-2s^-1
Argon (40Ar)	6.6E-26 kg	3.1424E6 Pm^-2s^-1
Methane (22)	27E-23 kg	1.617E3 Pm^-2s^-1
Co2	7.3E-23 kg	3.146E3 Pm^-2s^-1

This table shows the rates of escape of each particle in units of particles per meters squared per meters. Since we are assuming that the current lunar equilibrium is constant than we can assume that these escape rates are the same as the natural sources of the lunar atmosphere.

My final model is a simple set of Ordinary differential equations that represent the rates of change of individual compounds in the atmosphere.

$$(He)d/dt = \alpha_1 - \theta'_{escape(He)} + U_{He} \tag{4}$$
$$(N)d/dt = \alpha_2 - \theta'_{escape(N)} + U_N \tag{5}$$
$$(H)d/dt = \alpha_3 - \theta'_{escape(H)} + U_H \tag{6}$$
$$(Ar)d/dt = \alpha_4 - \theta'_{escape(Ar)} + U_{Ar} \tag{7}$$
$$(Me)d/dt = \alpha_5 - \theta'_{escape(Me)} + U_{Me} \tag{8}$$
$$(Co2)d/dt = \alpha_6 - \theta'_{escape(Co2)} + U_{Co2} \tag{9}$$
$$(H2S)d/dt = U_{H2S} \tag{10}$$
$$(H2O)d/dt = U_{H2O} \tag{11}$$
$$(CO)d/dt = U_{CO} \tag{12}$$

In these equations we define α_1 through α_6 as the natural sources of each gas(in this model they are the same as the natural sinks). Then we add $U_{AtomicSymbol}$ representing the human perturbation to that element. The rates of these perturbations can be found in table 2. Lastly, the values of $\theta'_{escape()}$ are representative of a new post human change in the rate of escape. As was indicated in the thermal escape section and seen in the positive relationship between particle density and escape rates of Jean's equation we can intuitively assume that the rate of escape will go up to slightly compensate for human presence.

Future Research

If given the change to continue this research I would attempt to calculate the change thermal escape rates, and subsequent particle evaporation after human presence. However, I believe that more data needs to be collected on the human off gassing before this model will be representative of true dynamics.

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