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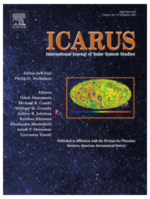

# Contributions of solar wind and micrometeoroids to molecular hydrogen in the lunar exosphere

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## ABSTRACT

We investigate the density and spatial distribution of the $H_2$ exosphere of the Moon assuming various source mechanisms. Owing to its low mass, escape is non-negligible for $H_2$. For high-energy source mechanisms, a high percentage of the released molecules escape lunar gravity. Thus, the $H_2$ spatial distribution for high-energy release processes reflects the spatial distribution of the source. For low energy release mechanisms, the escape rate decreases and the $H_2$ redistributes itself predominantly to reflect a thermally accommodated exosphere. However, a small dependence on the spatial distribution of the source is superimposed on the thermally accommodated distribution in model simulations, where density is locally enhanced near regions of higher source rate. For an exosphere accommodated to the local surface temperature, a source rate of $2.2\,\mathrm{g\,s^{-1}}$ is required to produce a steady state density at high latitude of $1200\,\mathrm{cm^{-3}}$. Greater source rates are required to produce the same density for more energetic release mechanisms. Physical sputtering by solar wind and direct delivery of $H_2$ through micrometeoroid bombardment can be ruled out as mechanisms for producing and liberating $H_2$ into the lunar exosphere. Chemical sputtering by the solar wind is the most plausible as a source mechanism and would require 10–50% of the solar wind $H^+$ inventory to be converted to $H_2$ to account for the observations.

## 1. Introduction

It has been confirmed that water exists in permanently shadowed regions of the lunar poles (Colaprete et al., 2010). However, the source of the water remains an open question. Several candidate sources exist and may each contribute including comets, micrometeoroids, internal water, and solar wind (Arnold, 1979). The solar wind ions comprise primarily protons. Once steady state is achieved, there must be a balance in the influx of protons and the outflow of hydrogen. However, there are multiple pathways for the outflow of hydrogen. Some of those pathways have been observed by spacecraft. In this paper, we quantify the amount converted to $H_2$. This further constrains the amount of solar wind protons that is available to be converted to water, and potentially migrate to the poles.

$H_2$ has been detected spectrally in the lunar exosphere by the Lyman Alpha Mapping Project (LAMP) on NASA's Lunar Reconnaissance Orbiter (LRO). Initially, it was detected in the vapor plume emanating from the Lunar CRater Observation and Sensing Satellite (LCROSS) impact into the permanently shadowed Cabeus crater (Gladstone et al., 2010). Modeling of the propagation of the vapor plume indicated that 110 kg of $H_2$ was released by the impact (Hurley et al., 2012). The analysis suggested that an energy source such as an exothermic reaction of two hydrogen atoms adsorbed to the surface forming $H_2$ via a grain-catalyzed reaction was consistent with the perceived partition of energy from the impact.

Later Stern et al. (2013) detected $H_2$ in the lunar exosphere by integrating observations made at high latitudes on the nightside of

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the Moon from the first 3.5 years of LAMP data. They determine a column density of $5.9 \times 10^9\,cm^{-2}$, or an equivalent surface density of $H_2$ of $1200 \pm 400\,cm^{-3}$. This is consistent with the previous upper limit set by Feldman and Morrison (1991) of $< 9000\,cm^{-3}$ based on UV observations from the Apollo 17 orbiter. The Stern et al. (2013) detection of $H_2$ provides an average amount over an extended region of the Moon. Without spatial or temporal resolution, the observation is not able to distinguish between various sources and release mechanisms, but does give a useful upper boundary to the global steady state release of $H_2$.

In addition, $H_2$ has been detected through mass spectrometry in the vicinity of the Moon. The Moon Impact Probe (MIB) released from the Chandrayaan-1 orbiter carried a neutral mass spectrometer, CHandra's Altitudinal Composition Explorer (CHACE) (Sridharan et al., 2010). The $H_2$ detected along the sub-satellite trajectory on the lunar dayside demonstrated higher surface density near the pole than at low latitudes (Thampi et al., 2015). The estimated surface density at high southern latitude on the dayside was $825\,cm^{-3}$, consistent with the Stern et al. (2013) nightside polar averages at a lower surface temperature.

More recently, Halekas et al. (2015) analyzed LADEE NMS data using the ion mode to infer the density of the $H_2$ exosphere. Using the specifics of the geometry of the convection electric field and the viewing geometry of the NMS, the analysis is sensitive to ions produced from exospheric neutrals, and therefore traces exospheric density. However, the observations necessarily convolve the ionization production process and the column density along the electric field direction.

Water and $H_2$ share the same potential sources on the Moon. Solar wind implanted hydrogen has been considered the most likely source owing to the steady stream of hydrogen incident on the Moon. However, micrometeoroids bring some volatiles with them that would be released on impact upon the surface of the Moon. The Neutral Mass Spectrometer (NMS) onboard the Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft detected an increase in exospheric water associated with lunar encounters with meteor storms (Mehdi Benna, personal communication).

A solar wind proton that encounters the Moon is implanted into the regolith grain it hits. At energies of $1\,keV\,amu^{-1}$, protons penetrate a few 10 s of nm into the rim of the grain. Although most of the incident ions are neutralized on contact, the mission Kaguya measured that 0.1–1% of SW protons are backscattered immediately from the surface (Saito et al., 2008). These percentages have also been confirmed by NASA's Acceleration, Reconnection, Turbulence, and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS) spacecraft (Halekas et al., 2013). An additional population of energetic neutral hydrogen that has been reflected from the surface of the Moon has been observed by SARA on ISRO's Chandrayaan-1 (Wieser et al., 2009) and Interstellar Boundary Explorer (IBEX) (McComas et al., 2009; Funsten et al., 2013; Allegrini et al., 2013). IBEX observations are consistent with 10% of solar wind protons being converted to energetic neutral atoms (ENA). SARA's observations show up to 20%. Thus, only 10.1–21% of the incident flux of solar wind protons has been directly accounted for by observations. This leaves 79–90% of solar wind inventory unobserved.

Hodges (2011) predicts that nearly all of the solar wind can be converted to neutral H that immediately diffuses out of the regolith while still being consistent with ENA, far ultraviolet (FUV), and ion observations. In that model, the energy distribution of the H is such that most of the atoms are escaping the Moon, however at energies below what is detectable by ENA instruments.

Returned lunar regolith from the Apollo missions contain hydrogen that has built up in the rims of regolith grains (Hintenberger et al., 1970; Leich et al., 1973). This reveals that, as expected from laboratory experiments (Lord, 1968; Zeller et al., 1966; Wehner et al., 1963), the lunar regolith acts as a sink for solar wind elements as small amounts accumulate in the rims until a steady state saturation level is achieved. For solar wind hydrogen, the saturation limit appears to be ~150 ppm in equatorial soils (DesMarais et al., 1974). Neutron detectors sense an overall decrease in epi-thermal neutron flux in the lunar polar regions (Feldman et al., 1998; Mitrofanov et al., 2010), which signifies an increase in hydrogen abundance near the poles. As this measurement cannot distinguish between binding states of hydrogen, it is not known whether this indicates an increased presence of implanted hydrogen, adsorbed water, or hydrated minerals at high latitudes.

This paper presents models of exospheric $H_2$ produced by various source and release mechanisms. The results are discussed in terms of how the likely sources and processes influence the distribution of exospheric hydrogen. Finally, we discuss how the various source and release mechanisms fit into the greater hydrogen and hydrologic cycle on the Moon.

## 2. Exosphere model

### 2.1. Model description

The exosphere model is a Monte Carlo model that follows particles as they hop along collisionless, ballistic trajectories in the lunar exosphere by following the equation of motion under gravity (Hurley, 2011; Killen et al., 2012) neglecting radiation pressure. The equation of motion is solved using a fourth order Runge–Kutta algorithm (Press et al. 1992) with 1-s time steps. The particles are originally released with a spatial and energy distribution representative of the assumed source. The source's distribution in phase space is extremely important, and is discussed in detail below.

Being a low-mass species, much $H_2$ escapes beyond the Hill sphere of the Moon, i.e., beyond the region where lunar gravity dominates the motion of the particles. In the model, when a particle reaches the Hill sphere at $35\,R_{moon}$, the model counts the particle as "escaping" and no longer traces the particle. Although these particles enter Cis-Lunar space and may return to the Moon, they are not expected to represent a significant portion of the $H_2$ at very low altitude, where measurements occur (<200 km). The model also calculates the loss due to photodissociation for any particle that is in sunlight for each time step. Using the Huebner et al. (1992) photodissociation rate for quiet Sun conditions, photodissociated particles are removed from the simulation.

Particles that reencounter the surface of the Moon interact with the regolith. Possible interactions include dissociative adsorption, thermal accommodation, or elastic collisions. We assume that $H_2$ does not adsorb to the surface, thus set loss from dissociative adsorption to zero. Also, this means that the particle is re-released in the model immediately on the next time step. The model parameterizes the energy exchange between the $H_2$ molecule and the surface every time a particle encounters the surface using an accommodation coefficient. The actual thermal accommodation of $H_2$ interacting with lunar regolith is poorly constrained. For the runs presented here, we assume 100% thermal accommodation, meaning the particles are released with no memory of their incident velocity and have a distribution representative of a Maxwell–Boltzmann distribution at the local surface temperature. The local surface temperature is implemented in the model using an empirical function (Hurley et al., 2015).

The model neglects energy exchange between translational, vibrational, and rotational degrees of freedom for the $H_2$ molecules. By allocating all of the energy as translational, the model slightly overestimates the velocity of the molecules. The net result would be an overestimate of escape, and therefore a lower density.

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