Lunar Surface, Interaction of the Solar Wind with Upper Regolith

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Definition

Protons of the solar wind can implant into the lunar near-surface region into the top 100 nm. The solar wind can either quickly diffuse out of the surface or be retained, depending on the surface temperature and activation energy of the surface material. Understanding the activation energies upon implantation can provide further information on hydrogen-retention times.

Implantation of protons

The description of the solar wind interaction with the Moon has been described in two ways: (i) a kinetic approach (Whang 1969); and (ii) a continuous fluid approach (Wolf 1968; Spreiter et al. 1970). While both have certain dynamics not currently observed (e.g., trailing shock, flow alignments), the real solar wind flow structure is dependent on a number of parameters, such as thermal speed and characteristics of the plasma flow (Bosqued et al. 1996).

The solar wind comprised of protons and electrons eject from the Sun at a velocity of ~400 km/s. At 1 AU, the density of solar wind is approximately 5 ions per cubic centimeter, containing ~95% proton, 2 – 4% He^{++}, and the remainder consisting of heavier ion species, such as O^{7+} (Killen et al. 2012; Szabo 2015; Tang et al. 2021). However, such velocity and density can be variable, such as during coronal mass ejections (CMEs), where the speed can become nearly twice the nominal values, and the density can be a factor of 10 times larger. The relative concentration of heavy ions (He^{++}, O^{7+}, etc.) can increase as much as 20% (Farrell et al. 2015). The Moon being a relatively airless body has its dayside surfaces directly exposed to this fast-streaming plasma while shadowed/nightside surfaces are not (as such, the plasma concentrations here are 1/500th of the nominal solar wind) (Farrell et al. 2008; Holmström et al. 2012).

The implantation of solar wind protons can occur in a variety of pathways (see Figure 1). Saito et al. (2008) suggests that ~1% of the incoming protons are reflected back into the solar wind, though this reflected ion factor can increase up to 50% over magnetic anomalies (Lue et al. 2011; Poppe et al. 2012). Observations suggest that ~20% of the incoming solar wind is re-emitted as low energy neutral hydrogen (McComas et al. 2009; Hodges 2011; Futaana et al. 2012). Several studies (Zeller et al. 1966; Pieters et al. 2009; McCord et al. 2011) state that a fraction of the incoming protons may implant into the regolith with O atoms in the oxide-rich regolith to form surficial OH (exogenically-created).

Hodges (2011) described that 1 keV solar wind protons will undergo a charge exchange with the neutral surface and implant as H in the top 100 nm of the regolith. The diffusion time back out into free space is strongly dependent on surface temperature and "*trapping defects*" (i.e., crystal lattices, porosities) (Dyar et al. 2010; Starukhina 2012), where the crystallinity to locally trap a free H is represented by the activation energy U, and values > 1 eV are where the H is trapped and have difficulty migrating (Farrell et al. 2015). However, low values of U associated with a mostly uniform crystal lattice could lead to faster H diffusion even at relatively low temperatures. Farrell et al. (2015) note several characteristics of diffusion times, such as: (i) the equatorial lunar surface has H diffusion (retention) times span many orders of magnitude due to the variable temperature range (10^{-2} s in warmer regions and 10^{15} s in cold (near-terminator) regions); (ii) defect-free crystals very quickly diffuse incident protons back into free space, returning back into space as H (McComas et al. 2009) or H_2 (Starukhina 2006); (iii) if the lattice has large vacancies or hole-type defects, any H in this crystal will have difficulties migrating, up to 10^6 s even in the warmest locations (H-retaining); and (iv) some regions (U = 0.5 eV) can easily emit H in smaller timescales (above 300 K), but become H-retentive if below 170 K, ultimately giving a diurnal effect (Sunshine et al. 2009). Therefore, incident solar wind protons may implant in low, moderate, or high U-valued regions depending on the surface temperature and nature of regolith crystallinity defects (Farrell et al. 2015).

In experimental conditions conducted by Tang et al. (2021), olivine, pyroxene, plagioclase, and volcanic glasses were irradiated with 7 keV H^+ (at 10^{17} ions/cm^2) to simulate the solar-wind proton implantation process on the Moon. The infrared spectral properties were compared before and after H^+ implantation, confirming that OH forms in the minerals and glass after implantation, with a comparably higher amount of OH/H_2O in plagioclase. Tang et al. (2021) suggested that plagioclase can capture more H^+ than other silicate phases. This in turn verifies that H^+ implantation is affected by crystal structure.

Amount of OH

Although the lunar surface has been irradiated by solar wind ions for billions of years, the overall amount of OH is well below saturation (Farrell et al. 2015). Saturation occurs when every O in the regolith has an associated H in the top 100 nm of exposed regolith at ~5 x 10^{28} / m^3 (Starukhina 2001). IR remote sensing values have a range of 10^{23} – 10^{25} /m^3 depending on grain size and regolith composition (Clark 2009; Dyar et al. 2010). Say if 100% of incoming solar wind were immediately retained (no diffusion), then the saturation time would be ~200 years (Farrell et al. 2015).

Net loitering values, however, are inconsistent since such high retention rates should have created a saturated surface in less than 1000 years of exposure. It is more likely that such H retention may be offset by other loss processes, such as sputtering and impact vaporization (Housley et al. 1974). From H-retention / impact ratio scenarios (see Farrell et al. 2015), observations may explain why lunar highland regions tend to have more H relative to mare. Further evidence of this impact-varying effect is described in Pieters et al. (2009).

Complimentary work can be found in Poston et al. (2012, 2013) where they suggest that the incoming protons are captured by the regolith oxides to chemically form OH and then follow migration, diffusion, and retention paths, including the creation (and release) of water at the surface via OH + OH desorption.

Alteration of the Regolith

Once solar wind implants H^+ reacting to form OH^- or H_2O, the implanted granular surface become reduced, whether the H_2O subsequently escapes from the grain (Housley et al. 1974). Housley et al. (1974) suggests that the production of Fe metal during the formation of lunar breccias are dependent on solar wind reduction at the lunar surface. They also suggest that isotopic fractionation of certain elements is dependent on solar wind processes. That is, solar wind sputtering is the major process by which mass is lost from the Moon and produce C and S fractionation, which volatilize on grain surfaces during micrometeorite impacts.

Wind Spacecraft

The Wind spacecraft, launched in November 1994, passed behind the Moon on December 27th, 1994 and remained in its optical shadow for ~41 minutes. The Solar Wind Experiment (SWE) on the Wind spacecraft is an integrated set of sensors which is designed to investigate outstanding problems in solar wind physics. Such key parameters (e.g., velocity, density, thermal properties) of the solar wind ions have been extracted from this experimental component of the spacecraft (Ogilvie et al. 1995; Szabo 2015). Such an instrument derives from the Voyager plasma instrument (Bridge et al. 1977).

The Moon was immersed in the interplanetary medium and solar wind, collected by the Wind/3DP experiment (Bosqued et al. 1996). The nature of the flow with details of the electron and ion plasma parameters in various regions are described in Holmström et al. (2012) and Szabo (2015). This study showed that plasma densities and magnetic field magnitudes vary, and the such Wind results are compared with fluid-like descriptions of the global Moon-solar wind interaction.

The Apollo SWC Experiment

The Solar Wind Composition (SWC) experiment was deployed on the first five Apollo lunar landing missions. This experiment was designed to measure elemental and isotopic abundances of the light noble gases in the solar wind, including investigating the time variations in the composition (Geiss et al. 2004). The Apollo crews deployed a foil at their respective landing sites, and solar wind particles were collected for time periods ranging from 77 minutes (Apollo 11) to 45 hours (Apollo 16). These foils were returned to Earth for analysis in ultra-high vacuum mass spectrometer systems. Geiss et al. (2004) summarized average fluxes of the isotopes He, Ne, and Ar. Definite variations were found for the $^{4}He/^{3}He$ and He/Ne ratios. From Geiss et al. (2004), the weighted average solar wind abundances were (to a 2σ level): $^{4}He/^{3}He = 2350 \pm 120$, $^{4}He/^{20}Ne = 570 \pm 70$, $^{20}Ne/^{22}Ne = 13.7 \pm 0.3$, $^{22}Ne/^{21}Ne = 30 \pm 3$, $^{20}Ne/^{36}Ar = 49 \pm 7$ and $^{36}Ar/^{38}Ar = 5.4 \pm 0.3$.

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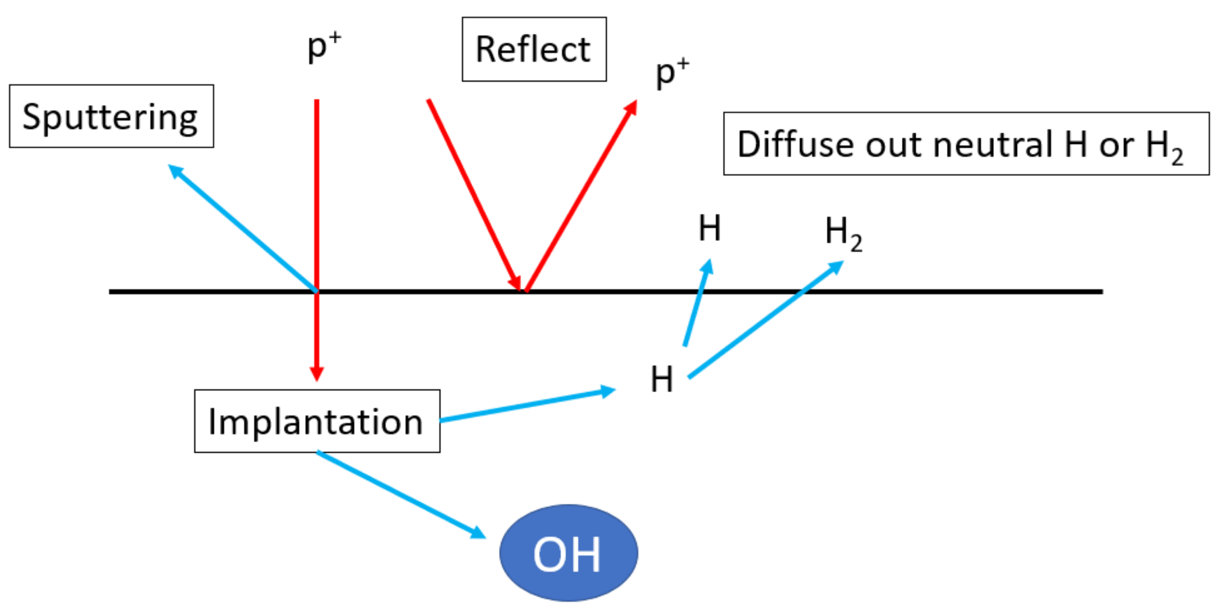

Figure 1: Illustration of possible surface-subsurface interactions for an implanted solar wind proton. Adapted from Farrell et al. (2015).