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The gas-surface interaction of a human-occupied spacecraft with a near-Earth object

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Abstract

NASA's asteroid redirect mission (ARM) will feature an encounter of the human-occupied Orion spacecraft with a portion of a near-Earth asteroid (NEA) previously placed in orbit about the Moon by a capture spacecraft. Applying a shuttle analog, we suggest that the Orion spacecraft should have a dominant local water exosphere, and that molecules from this exosphere can adsorb onto the NEA. The amount of adsorbed water is a function of the defect content of the NEA surface, with retention of shuttle-like water levels on the asteroid at 10^{15} H_2O's/m^2 for space weathered regolith at $T \sim 300$ K.

Keywords: Asteroid; Water; Orion

1. Introduction

In 2012, a Keck Institute for Space Studies panel presented a unique concept for a human visit to a near-Earth asteroid (NEA), where the asteroid (or part of an asteroid) is captured, returned, and safely placed into lunar orbit. The object would then be visited multiple times by humans onboard the Orion multi-purpose crewed vehicle or MPCV (Asteroid Retrieval Feasibility Study, http://www.kiss.caltech.edu/study/asteroid/asteroid_final_report.pdf). This Asteroid Retrieval Mission (now called Asteroid Redirect Mission) is a primary Human Exploration initiative with the launch of a capture spacecraft scheduled for as soon as 2020.

The current mission design has a capture spacecraft powered by solar electric propulsion obtaining a ~ 4-m diameter boulder of a larger asteroid. This boulder will then be returned to cis-lunar space in the mid 2020s. Fig. 1 illustrates the human-occupied Orion spacecraft and ESA Service Module (ESM) in proximity with the captured airless body. The ARM Formulation Assessment and Support Team released their draft report identifying NEA 2008 EV_5 as a possible target (see http://www.nasa.gov/feature/arm-fast for more details).

Much like the Moon itself, after many years of exposure to the space environment (impact gardening, plasma sputtering), the weathered surface of the asteroid should have increased gas sorbency. A human system in proximity to the asteroid can thus alter the natural state of the interface at the atomic level by forward adsorption of spacecraft-originating outgassing molecules. In this work, we will examine the interaction of an outgassing Orion spacecraft

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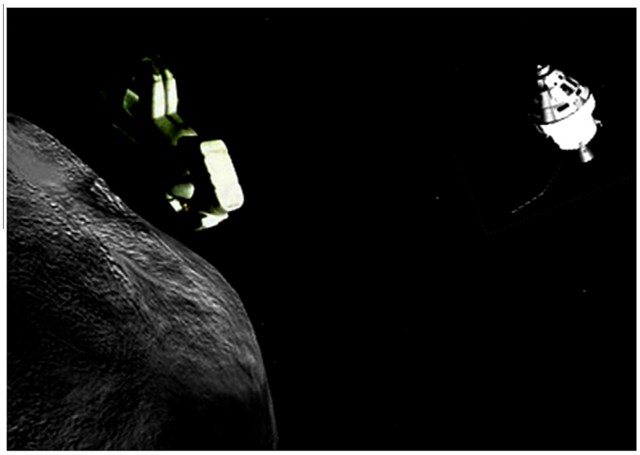

Fig. 1. An illustration of the Orion spacecraft (upper right) in the near-vicinity of the captured asteroid block (lower left). The asteroid block is ~5 m in size and the Orion spacecraft is ~200 m in distance away from the astronaut/asteroid.

with the asteroid. We will estimate the level of water anticipated that can be adsorbed onto the NEA surface – using the space shuttle outgassing as an analog. We demonstrate that the amount of molecular material that is adsorbed is a function of both NEA surface temperature and surface defect content; the latter being a function of the amount of previous space weathering the object has undergone. As recently described, (Dyar et al., 2010; Hibbitts et al., 2011; Poston et al., 2013, 2015), vacancy defect sites increase adsorption potentials and thus can trap water molecules for anomalously long times (Müller et al., 1996).

2. The water source: the space shuttle as an analog for Orion

The outgassing of a human occupied spacecraft was monitored and quantified during the Space Shuttle's SpaceLab-2 mission. Paterson and Frank (1989) examined the water ion cloud that forms about the shuttle from charge exchange processes with ionosphere gases using a plasma electrostatic analyzer on the Plasma Diagnostics Package sub-satellite in orbit about the shuttle. The water ion levels were found to be in excess of $10^4/cm^3$ in the anti-ram (tail) direction of the shuttle, and are consistent with the presence of a water neutral cloud in the near-shuttle vicinity with a concentration of $n_w > 10^9/cm^3$. Their modeling of the cloud indicates that the water neutral density is reduced to $n_w \sim 10^6/cm^3$ at a distance of 1 km from the shuttle, $n_w \sim 10^4/cm^3$ at 2 km from the shuttle and $n_w \sim 1/cm^3$ at 8 km from the shuttle (Paterson and Frank, 1989; Fig. 5).

While we do not know a priori the Orion water emission levels, we should assume that any spacecraft carrying humans will likely be providing a water atmosphere far greater in content than any atmosphere/exosphere provided by the NEA. For example, the lunar surface has an exospheric density of $n_{Moon} \sim 10^5/cm^3$ (see Stern (1999) and references therein). Much of this lunar atmosphere consists of gravitationally bound Argon-40. In the low g environment of a ~ 4-m asteroid, such heavy species would no longer be bound, and thus the asteroid escaping exosphere (called a corona (Morgan and Killen, 1998)) would be of even lower concentrations. As an example, for a dormant NEA, impact vaporization is expected to release neutral atoms at 10^{-15} kg/m^2 s or $\sim 10^{10}$ molecules/m^2 s (Cintala, 1992). Solar wind plasma sputtering would also occur at the surface at a rate of $R = FY$, with F being the solar wind flux at $5 \times 10^{12}/m^2$ s and Y the sputtering yield for silica at 0.03 (Johnson, 1990). This second process releases 10^{10-11} molecules/m^2 s. Since these molecules escape the small body at their ejection velocity (nominally, $\langle v \rangle \sim 2$ km/s for $T = 4000$ K impact vaporization and $\langle v \rangle \sim 3$ km/s for $T \sim 10{,}000$ K sputtering), the time-stationary density of the surface-released atoms is very low: $n_{nea} = F/\langle v \rangle \sim 10$–$100/cm^3$. We thus conclude that the atmosphere of the human-occupied spacecraft ($n_w \sim 10^9/cm^3$) far exceeds by many orders of magnitude that liberated naturally from the small body ($n_{nea} \sim 10^2/cm^3$).

3. Water sticking to the asteroid surface

Recent temperature-programmed desorption (TPD) results (Poston et al., 2013, 2015) of water release from simulant and lunar samples are found to be describable by the first-order ($n = 1$) Polanyi-Wigner adsorption equation. The derived residency time of water molecules on a surface is:

$$\tau = \tau_o \exp(U/T) \quad (1)$$

where $\tau_o \sim 10^{-13}$ s is the inverse of the quantum frequency for the trapped energy state of the molecule in the inter-atomic potential (see Hunten et al., 1989; Fig. 13), U is the adsorption activation energy in eV, and T is the surface temperature in eV. The value of U ranges from low values <0.3 eV for uncomplicated surface crystals to >1 eV for surface with vacancy-type defect sites (i.e., possessing relatively deeper adsorption trapping well). The TPD lab work of Poston et al. (2013) quantified a population of high U value adsorption sites ($U \sim 0.6$–1.2 eV) on lunar simulant and albite.

Fig. 2 shows a water molecule residency time as a function of temperature and activation energy value. For unweathered or mildly weathered surfaces ($U < 0.3$ eV), the water residency time is small: less that a second. However, for surfaces with a large population of large-U valued adsorption sites ($U > 0.65$ eV), the water residency time or 'sticking time' can exceed 10^5 s for $T < 200$ K. For residency times longer than about 10^5 s, photo-dissociation of water molecules (Crider and Vondrak, 2000; DeSimone and Orlando, 2015) will become the dominant water loss process limiting surface residency times.

Fig. 3 shows the surface water molecules retained as a function of temperature and activation energy value. We assume a spacecraft-originating water flux of