THE ORIGIN OF VESTA’S ASYMMETRIC DISTRIBUTION OF HYDROGEN SIGNATURES AND HYDRATED MINERALS. J. K. Steckloff 1,2, D. Goldstein3, P. Varghese1, L. Trafton 3, 1University of Texas at Austin, Department of Aerospace Engineering and Engineering Mechanics, 2617 Wichita St., Austin, TX 78712, USA (stecklff@utexas.edu) 2Planetary Science Institute, 1700 East Fort Lowell, Suite 106, Tucson, AZ 85719, USA 3University of Texas at Austin, Department of Astronomy, RLM 16.326, Austin, TX 78712, USA

Introduction: The Dawn mission to Vesta found evidence of aqueous alteration on its surface. The Dawn VIR instrument detected terrains rich in OH groups[1] that coincide with terrains that the GRaND instrument found to be rich in hydrogen[2]. Although Vesta has no permanently shadowed regions[3], the Vesta subsurface is cool enough to store water ice for billions of years [3,4].

Other large, airless bodies in the inner solar system show similar evidence of water. Water ice has been found in permanently shadowed craters on Mercury[5–9], the Moon[10–15], and Ceres[16,17] in latitudinal trends that suggest water’s distribution of water on these bodies is largely controlled by solar insolation flux. In stark contrast, Vesta’s hydrated and H-rich terrains are localized, but do not follow latitudinal trends[1,2]. This enigmatic distribution has been attributed to stochastic delivery of these hydrated materials by carbon-rich impactors[18]. Nevertheless, Vesta and Ceres experience the same impactor population, suggesting that, if Vesta’s hydrated mineral distribution is solely due to impacts, similar patterns should be seen Ceres.

We instead propose that Vesta’s non-latitudinal distribution is the direct result of its smaller size, which precludes the retention of a bound H₂O exosphere. Exospheres facilitate water migration about the surface, distributing water both longitudinally as the body rotates, and latitudinally as the water migrates toward the poles over diurnal timescales[19,20]. Such exospheres can form following large, water-rich impacts[19–21], impacts into water-bearing surface terrains, or from the direct sublimation of surface water ice.

Bodies Capable of H₂O Exospheres. To form an H₂O exosphere, a body must be warm enough for ice to sublimate during the day, and large enough to prevent the escape of the resulting water vapor. From kinetic-molecular theory, one may describe the expected time that a typical water molecule resides in a condensed ice phase, prior to sublimating to gas as[22,23]:

\[ \tau_{\text{res}} = \frac{u_0}{\eta \varepsilon k_B T} \]

where \( \tau_0 \) is the oscillation period of a molecule on the surface perpendicular to the surface, \( u_0 \) is the molecular binding energy, \( k_B \) is Boltzmann’s constant, and \( T \) is the surface temperature. For a water molecule in an ice lattice, these values are \( \tau_0 = 5.0 \times 10^{-13} \text{ s} \) and \( u_0 = 6.64 \pm 0.02 \times 10^{-20} \text{ J} \) for unannealed H₂O ice and \( u_0 = 7.00 \pm 0.07 \times 10^{-20} \text{ J} \) for annealed H₂O ice[24]. Each airless solar system body has a unique residence time determined by its peak blackbody temperature over the course of a rotation:

\[ T_{\text{peak}} = \left( \frac{1 - A}{\varepsilon} \right) \left( \frac{L_{\text{solar}}}{4\pi r^2} \right)^{\frac{1}{2}} \]

where \( A \) is the surface’s Bond albedo, \( L_{\text{solar}} \) is the solar luminosity, \( r \) is the heliocentric distance, \( \varepsilon \) is surface’s the emissivity, and \( \sigma \) is the Stefan-Boltzmann constant. The emissivity \( \varepsilon \) of typical geologic materials are close to unity. To form an H₂O exosphere, an airless body’s residence time must be significantly shorter than the length of a day, otherwise water would condense into a permanent, high-albedo frost layer. There are only four large airless bodies in the inner solar system for which this condition is met, allowing H₂O exospheres to form: Mercury, the Moon, Ceres, and Vesta (see fig. 1).

Figure 1: The rotation periods of airless bodies, plotted with residence time of water ice as a function of albedo.

Bodies Large Enough to Retain Exospheres. Additionally, a body must be sufficiently large to gravitationally retain water vapor, to prevent rapid ballistic escape of exospheric H₂O. One can compute the mean-magnitude thermal speed of a water molecule on the illuminated side by balancing solar heating with radiative heat loss (averaged over the illuminated side of the body):

\[ v_{\text{th}} = \sqrt{\frac{8 k_B T_{\text{avg}}}{\pi m n}} \]

\[ T_{\text{avg}} = \left( \frac{1 - A}{2\varepsilon \sigma} \right) \left( \frac{L_{\text{solar}}}{4\pi r^2} \right)^{\frac{1}{2}} \]

where \( T_{\text{avg}} \) is the average temperature on the illuminated side of the body, and \( m \) is the mass of a water molecule. Comparing this to the surface escape speed
we find that Mercury and the Moon can clearly retain these water molecules, while Ceres and Vesta have thermal speeds comparable to their surface escape speeds.

<table>
<thead>
<tr>
<th></th>
<th>Mercury</th>
<th>Moon</th>
<th>Ceres</th>
<th>Vesta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. H$_2$O speed (m/s)</td>
<td>743-824</td>
<td>611-617</td>
<td>473-492</td>
<td>478-503</td>
</tr>
<tr>
<td>$v_{min}$ (m/s)</td>
<td>4,250</td>
<td>2,380</td>
<td>510</td>
<td>360</td>
</tr>
</tbody>
</table>

Table 1: H$_2$O speeds and surface escape speeds.

Refining this approach, we compute the thermal speed of a water molecule as a function of angular distance from the subsolar point for both Ceres and Vesta. Since H$_2$O condenses into surface frost on the night side of these bodies and sublimates at the dawn terminator[20,21], we also compute the minimum speed needed to reach various points across the illuminated surface of the body from the dawn terminator at the equator.

For Ceres, we find that the thermal velocity of a water molecule is usually less than the surface escape speed, except for a region within ~40 degrees of the subsolar point. Additionally, the thermal speed at/near the dawn terminator is sufficient to send water molecules anywhere across the illuminated side of Ceres, with any molecules that land near the subsolar point having a high probability of escaping. Nevertheless, this escape hatch is small enough that Ceres should be able to retain an H$_2$O exosphere for many diurnal cycles (fig. 2).

Figure 2: The thermal speed of water on Ceres, and minimum speed to hop from dawn terminator at 2.7 AU.

Unlike Ceres, on Vesta the thermal speed of H$_2$O upon leaving the surface is always greater than the surface escape speed, except for a thin ribbon along the terminator, leading to rapid ballistic escape of any water molecules. Confounding this loss, the thermal speed near the terminator is sufficient to send water molecules anywhere on Vesta’s surface. Thus, any water molecules not directly ejected from the surface would likely make a few ballistic hops from the dawn terminator before striking a surface sufficiently warm to eject it. As a result, Vesta cannot retain an H$_2$O exosphere (fig. 3).

Figure 3: The thermal speed of water on Vesta, and minimum speed to hop from dawn terminator.

Conclusions: Given that Vesta and Ceres experience the same impactor population, the mechanism causing Vesta to lack a latitudinal trend in its water/hydrated mineral distribution is likely intrinsic. Vesta, like Mercury, the Moon, and Ceres, is warm enough to form an H$_2$O exosphere, but is too small to retain it. This precludes exospheric dynamics from smoothing Vesta’s water into the expected latitudinal trend. Instead, water and hydrated minerals on Vesta are either directly delivered to the surface as impact ejecta, or form from impact-delivered water directly striking Vesta’s surface, producing an asymmetric distribution of these features, in lower concentrations than are found on Ceres[1,2,17].


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