ANALYTICALLY DETERMINING THE SHAPE, STRUCTURE, AND DYNAMICS OF VOLATILE-DRIVEN EXOSPHERES ON AIRLESS BODIES. J. K. Steckloff[1,2], D. B. Goldstein[1] L. M. Trafton[3], P. L. Varghese[1], [1]University of Texas at Austin, Department of Aerospace Engineering and Engineering Mechanics, 2617 Wichita Street, Stop C0600, Austin, TX 78712 (steckloff@utexas.edu), [2]Planetary Science Institute, Tucson, AZ, [3]University of Texas at Austin, Department of Astronomy, 2515 Speedway, Stop C1400, Austin, TX 78712

Introduction: The majority of objects in the Solar System lack thick atmospheres. Nevertheless, many of the nominally "airless" bodies in our Solar System can and do possess tenuous, often temporary surface-bound exospheres composed of common volatile materials. The shape, structure, and dynamics of these exospheres are sensitive to the physical properties, composition, and location of their host body. For example, gases that condense onto the nighttime surface of a refractory body (e.g., argon or water on the Moon) tend to form a narrow exosphere in the morning [1-3], that runs from pole to pole [3]. However, the location of this morning exosphere is sensitive to the thermal conditions of the body. Bodies with volatile-rich (i.e., icy) surfaces form global exospheres with a sublimative mass flux and surface vapor pressure that depend on local thermal conditions. Furthermore, photodestruction and ballistic escape eliminate exospheres at rates that depend on solar insolation conditions and physical properties of the object respectively.

Because continuum fluid mechanics (e.g., Navier-Stokes equations) break down for weakly collisional "fluids" such as exospheres, determining the shape, structure, and dominant dynamical processes affecting such exospheres typically require the use of specialized numerical techniques. Typically, Direct Simulation Monte Carlo (DSMC) codes are used to simulate molecular motion and collisions between a statistically significant sample of exospheric molecules, from which the flow field, shape, structure, and dynamics of the exosphere is extrapolated statistically[4]. However, such techniques are notoriously computationally intensive, often required hundreds of CPUs on computing clusters to simulate exospheres.

Here we show that much of the structure, shape, and dynamics of exospheres around refractory, airless bodies can be determined numerically, without computationally expensive simulations. Though a careful choice of dominant processes affecting exosphere behavior (i.e., adsorption/desorption, photodissociation, and molecular ballistics), we can use simple numerical scripts that compute these properties from first principles. We then apply this technique to Mercury, the Moon, Ceres, and Vesta (hereafter, "MMCV"), to identify how the shapes, structures, and dominant loss mechanisms of their respective exospheres compare and differ.

Methods and Results: To study thermally induced exospheres (i.e., controlled by solar heating), we consider three first-order physical quantities that describe how exospheric structure and density vary over the surface of a body: adsorption/desorption (which populate an exosphere), and photodestruction and ballistic escape (which permanently remove exospheric molecules). We neglect solar wind and sputtering-induced exospheres, which, while important on some bodies, are nevertheless outside of our thermal considerations. We compute how the resulting exospheric structure, density, lifetime, and dynamic vary by species, heliocentric distance, and properties of the host body. We consider exospheres created by the most common volatile species in the inner solar system: H_2O, but note that this analysis is applicable to any neutral volatile species.

Adsorption/Desorption. Volatile species tend to "stick" to sufficiently refractory surfaces, adsorbing onto the cooler surfaces of airless bodies (e.g., at the poles and unilluminated hemisphere. Once absorbed, a molecule will remain until the surface becomes sufficiently warm to desorb from the surface (i.e., when the molecule's thermal energy is comparable to the surface binding energy). As an airless body rotates, there is a longitude on the illuminated hemisphere where adsorbed molecules tend to desorb into the exosphere.

We compute this desorption longitude by considering the expected amount of time that a molecule will remain adsorbed on the surface before desorbing is given by the residence time (τ_{res}):

$$\tau_{res} = \tau_0 e^{\frac{u_0}{k_B T}}$$

where τ_0 is the oscillation period of a condensed molecule on the surface perpendicular to the surface, u_0 is the energy released upon condensation (molecular binding energy), k_B is Boltzmann's constant, and T is the temperature of the surface[5,6]. For typical airless bodies, the nightside surface temperatures are sufficiently low (~100 – 110 K [7-8]) that associated residence times are many orders of magnitude longer than a diurnal cycle. Thus, we numerically integrate from the dawn terminator to identify the longitude at which a volatile (e.g., H_2O) will desorb from the surface. Since the thermal environment is a latitude dependent, the longitude of

desorption will depend on latitude. We apply this computation to MMCV (see figure 1), and find good agreement with DSMC simulations of the Moon[9].

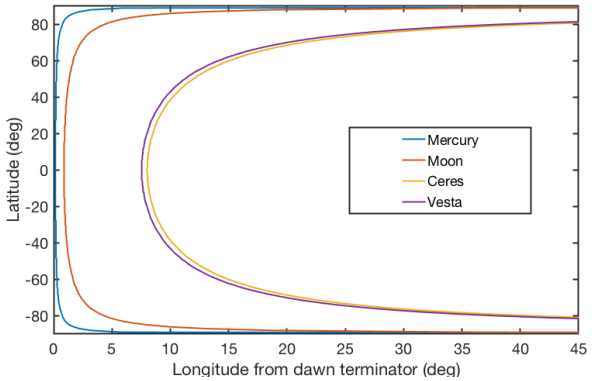

Figure 1: A computation of the desorption longitude as a function of latitude for MMCV. Note that Mercury and the Moon, as well as Vesta and Ceres, share similar desorption longitude profiles due to comparable rotation rates and thermal environments. The location where the desorption longitude streaks westward denotes the start of the polar cold traps.

Ballistic hop distance/duration. Desorbed molecules leave the surface with a speed determined by the surface temperature, according to the Maxwell-Boltzmann velocity distribution. Molecules leave the surface according to a Lambertian emission profile (emission angle proportional to cosine of angle relative to normal vector)[10]. To determine a typical desorbed molecule's "hop" distance (d_{hop}) and duration (t_{hop}), we use celestial mechanics to determine that molecule's elliptical trajectory as it moves about the body as a function of ejection angle and speed. Where the trajectory intersects the body is the molecule's landing spot. By integrating over the Maxwell-Boltzmann velocity distribution and Lambertian ejection angle distribution, we can determine the average hop distance and duration for each area element. Finally, integrating along the latitude-dependent longitude of desorption (see previous section) provides the average hop distance and hop duration.

When this hop distance is small relative to the size of the body, desorbed molecules land relatively near to the longitude of desorption. This results in a narrow, "banana-shaped" exosphere centered on the longitude of desorption (as is the case for H_2O on the Moon and Mercury). When the hop distance is large relative to the body size (as is the case for H_2O on Ceres and Vesta), the returning molecules can cover a significant fraction of the object's surface, resulting in an exosphere that is global in extent.

Ballistic escape. Molecules on the fast end of this distribution will likely exceed the surface escape speed of the body, and never fall back. The fraction of molecules lost via ballistic escape (f_{lost}) can be computed by integrating the Maxwell-Boltzmann distribution from the escape speed to infinity, and then integrate along the latitude-dependent longitude of desorption. To determine the typical ballistic residence time (t_{res}) in the exosphere (amount of time before a typical molecule escapes ballistically), one notes that $1 - f_{lost}$ molecules return to the surface, to be ejected again after t_{hop} has elapsed. Of these molecules, a further $1 - f_{lost}$ molecules return to the surface, to be ejected again after t_{hop} has elapsed. This results in an infinite series that can be easily solved to compute t_{res}.

Photodestruction. Solar photons of specific energies can break apart volatile molecules, which are unlikely to reform due to the tenuous nature of exospheres. The timescale of this photodestruction process is directly proportional to the intensity of sunlight, which follows an inverse-square law with heliocentric distance. Each volatile has a unique photodestruction timescale (t_{photo}), with the timescale for H_2O at 1 AU being approximately 25 hours[11].

Comparing t_{photo} with t_{res} allows one to determine which of these processes has a shorter timescale and therefore dominates the loss of exospheric molecules. The Moon and Mercury have high escape speeds and are close to the Sun, resulting in photodestruction dominating ballistic escape. The opposite is true for Ceres and Vesta, which are small and far from the Sun; ballistic escape dominates the loss of H_2O from these bodies' exospheres.

	Mercury	Moon	Ceres	Vesta
Surface escape speed (m/s)	4,250	2,380	510	360
Ballistic Residence (t_{res})	9.04×10^{18} yr	236,000 yr	13.8 hr	10.8 hr
Ballistic hop distance(d_{hop})	136 km	205 km	548 km	350 km
Object radius	2440 km	1737 km	473 km	263 km
Photodest. timescale (t_{photo})	~3.8 hr	~25 hr	~8.0 days	~5.8 days

Table 1: computed properties for H_2O on MMVC

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