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Exospheric escape: A parametrical study

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Abstract

The study of exospheres can help us understand the long-term loss of volatiles from planetary bodies due to interactions of planets, satellites, and small bodies with the interplanetary medium, solar radiation, and internal forces including diffusion and outgassing. Recent evidence for water and OH on the Moon has spurred interest in processes involving chemistry and sequestration of volatile species at the poles and in voids. In recent years, NASA has sent spacecraft to asteroids including Vesta and Ceres, and ESA sent Rosetta to comet 67P/Churyumov–Gerasimenko and the asteroids Lutetia and Steins. Japan's Hayabusa spacecraft returned a sample from asteroid Itakowa, and OSIRIS-REX will return a sample from a primitive asteroid, Bennu, to Earth. In a surface-bounded exosphere, the gases are derived from the surface and thus reflect the composition of the body's regolith, although not in a one-to-one ratio. Observation of an escaping exosphere, termed a corona, is challenging. We have therefore embarked on a parametrical study of exospheres as a function of mass of the exospheric species, mass of the primary body and source velocity distribution, specifically thermal (Maxwell-Boltzmann) and sputtering. The goal is to provide a quick look to determine under what conditions and for what mass of the primary body the species of interest are expected to be bound or escaping and to quickly estimate the observability of exospheric species. This work does not provide a comprehensive model but rather serves as a starting point for further study. These parameters will be useful for mission planning as well as for students beginning a study of planetary exospheres.
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Keywords: Exospheres; Escape; Volatiles

1. Introduction

Surface-bounded exospheres, i.e., atmospheres that are collisionless down to an object's surface, are the most common type of atmosphere in the Solar System. They are known to occur at the Moon, Mercury, and several outer-planet moons. The primary mechanisms for these exospheres vary for different objects and exospheric species, but include micrometeoroid impact vaporization, photon-stimulated desorption, ion-sputtering, and thermal desorption. Several objects, such as Enceladus (Porco and the Cassini Imaging Team, 2006), Europa (Roth et al., 2014), and Ceres (Kuppers et al., 2014) show evidence of active venting of water.

Typical exospheric studies usually take a tactical approach, focusing on one component at one body (e.g., sodium at the Moon, etc.), providing detail on the source mechanism, species trajectory, and subsequent surface processes. However, general exospheric trends across body sizes and process temperatures or source velocity distributions have not been fully explored in a systematic way. In other fields, such parametric studies have proven to be very valuable, providing a general understanding of the controlling variables for use in predictions of the resulting effects. For example, impact parameter studies (Gault et al., 1972;

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Housen and Holsapple, 2011) continue to provide insights on the impactor based on scalable cratering characteristics. An exosphere, although tenuous, may be gravitationally bound.

We have conducted a parametrical study of exospheres to distinguish between the bound and escaping components of exospheres (an escaping exosphere is commonly referred to as a corona). We describe a method for determining whether an exospheric species will gravitationally escape from a body as a function of the object radius and surface temperature, and the species mass and the source velocity distribution. We have considered Maxwellian velocity distributions at various temperatures and two sputter distributions, one consistent with sputtering from ices and one consistent with sputtering from regoliths. We do not consider specific source processes per se, but instead use the more general parameter of process temperature to identify a bounded vs. escaping exospheric component. We do not consider the subsequent interactions of released atoms or molecules with the surface for non-escaping species, since each interaction is specific to the atom/molecule and the surface. Despite the apparent limitations, the parametric study provides a scalable method to determine if a specific exosphere at a given body will remain primarily escaping or primarily bound – thereby identifying the body as a 'surface bounded exosphere'. Loss processes, such as photoionization, are not considered here.

2. Method

We assume that in a collisionless exosphere a neutral species escapes if it achieves escape velocity defined as:

$$v_{esc} = \left(\frac{2GM}{R}\right)^{1/2} = \left(\frac{8\pi}{3}G\rho R^2\right)^{1/2} \tag{1}$$

where G is the gravitational constant, R is the object radius, M is the object mass, and ρ is the object density.

For most processes, neutral species are ejected from the surface with a Maxwellian flux distribution in the form:

$$f(v) \propto v^3 \exp(-v^2/v_{th}^2) \tag{2}$$

where v_{th} is the thermal speed defined as $(2kT/m)^{1/2}$, k is Boltzmann's constant, T is the temperature, and m is the mass of the neutral species (Smith et al., 1978). The temperature could refer to the surface temperature, the temperature of the vapor cloud produced by impact vaporization, or other process that results in a thermal distribution (e.g., photon-stimulated desorption ejects Na with a ~1200 K Maxwellian distribution (Yakshinskiy and Madey, 2004).

We also consider a sputtering distribution in the form:

$$f(E) = \frac{EU^{\beta}}{(E+U)^{2+\beta}} \tag{3}$$

where U is the binding energy with the surface.

The sputtered flux $vf(v)$ would then be

$$vf(v) = vf(E)\frac{dE}{dv} \tag{4}$$

$$vf(v) \propto v^2 f(E(v)) \tag{5}$$

where

$$E \propto v^2 \tag{6}$$

and

$$U \propto v_{b0}^2 \tag{7}$$

Values of the binding energy, U, have been described as 0.052 eV consistent with sputtering from ice (Johnson et al., 2002) and 2–3 eV with sputtering from regolith (McGrath et al., 1986; Leblanc and Johnson, 2003), respectively. We have considered intermediate values of U as well. An empirical binding energy is often used for sputtering from planetary surfaces having been exposed to high fluences of charged particles resulting in chemically altered surfaces (Betz and Wehner, 1983; Roth, 1983). On planetary surfaces, an adsorbed layer, typically less than a monolayer in depth and bound more loosely than atoms in the crystalline lattice, can be desorbed by photons having energy of a few eV. The solar wind plasma energy, typically 1.5–10 keV, is deposited in the substrate and can therefore eject atoms from the crystalline lattice. Typical solar wind protons and ions have energy ~1 keV/AMU and penetrate tens of nm into the substrate (Barghouty et al., 2011). In addition to describing sputtering from icy bodies, the icy sputter velocity distribution (Eq. (3) with $\beta = 0.7$) has been used by some authors to simulate photon-stimulated desorption (e.g. Burger et al., 2010) because this velocity distribution is described by a cool core and a small extended tail (e.g. Yakshinskiy and Madey, 2000). For sputtering from rock, β in Eq. (3) is typically unity.

The fractional loss is given by

$$fracloss = \frac{\int_{vsec}^{\infty} vf(v)dv}{\int_{0}^{\infty} vf(v)dv} \tag{8}$$

3. Results

First we consider a Maxwell-Boltzmann flux distribution of particles (Eq. (2)) ejected from a body of radius, R, at temperature, T, for species of mass, m, in AMU (Smith et al., 1978). We show in Fig. 1 the temperature at which 50% of the ejected neutral species escape from a body as a function of the object radius and species mass. The body is assumed to have density 3.5 g cm^{-3}. A small body such as Phobos (radius = 11.27 km, v_{esc} = 11.39 m/s cannot hold any atmosphere at almost any temperature, whereas Earth-sized bodies are highly retentive for all gases except H, H_2, and He. Note that escape from an exobase at the top of an atmosphere is slightly different from escape from a surface-bounded exosphere (e.g. Chamberlain and Hunten, 1987). Notably, the gravity at the exobase is reduced from that at the planet's surface.

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