



Kinetic modeling of sodium in the lunar exosphere



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ABSTRACT

Our knowledge about the lunar environment is based on a large volume of ground-based, remote, and in situ observations. These observations have been conducted at different times and sampled different pieces of such a complex system as the surface-bound exosphere of the Moon. Numerical modeling is the tool that can link results of these separate observations into a single picture. Being validated against previous measurements, models can be used for predictions and interpretation of future observations results.

In this paper we present a kinetic model of the sodium exosphere of the Moon as well as results of its validation against a set of ground-based and remote observations. The unique characteristic of the model is that it takes the orbital motion of the Moon and the Earth into consideration and simulates both the exosphere as well as the sodium tail self-consistently. The extended computational domain covers the part of the Earth's orbit at new Moon, which allows us to study the effect of Earth's gravity on the lunar sodium tail.

The model is fitted to a set of ground-based and remote observations by tuning sodium source rate as well as values of sticking, and accommodation coefficients. The best agreement of the model results with the observations is reached when all sodium atoms returning from the exosphere stick to the surface and the net sodium escape rate is about $5.3 \times 10^{22} \text{ s}^{-1}$.

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1. Introduction

Analyzing emission spectra at the bright limb of the Moon, Potter and Morgan (1988a,b) discovered signatures of sodium in the exosphere of the Moon. This discovery has triggered a series of intensive ground based observations. Data collected during these observations cover a wide range of exospheric phenomena including variation of the exosphere with phase angle (Potter and Morgan, 1991, 1994, 1998; Stern and Flynn, 1995; Cremonese and Verani, 1997), the altitude distribution in the exosphere at lunar eclipse (Mendillo and Baumgardner, 1995; Mendillo et al., 1999), and the effect of meteor showers on the exosphere (Verani et al., 2001). Some of the recent ground-based observations of the lunar exosphere and sodium tail are presented by Mierkiewicz et al. (2006), Wilson et al. (2006), Matta et al. (2009), and Line et al. (2012).

Also the lunar environment is the object of intensive in situ study. A large amount of data has been collected during past and ongoing missions such as Kaguya (Kato et al., 2010), Chang'E (Huixian et al., 2005), Chandrayaan (Goswami and Annadurai,

2008), Lunar Prospector (Halekas et al., 2002, 2005; Richmond and Hood, 2008), Lunar Reconnaissance Orbiter (Chin et al., 2007), WIND (Ogilvie et al., 1996; Kellogg et al., 1996; Bosqued et al., 1996; Farrell et al., 1997; Clack et al., 2004; Owen et al., 1996), LCROSS (Shuvalov and Trubetskaya, 2008; Colaprete et al., 2010), and ARTEMIS (Sweetser et al., 2011; Sibeck et al., 2011; Angelopoulos, 2011). The list of new phenomena discovered during these missions includes direct scattering of solar wind protons from the surface (Saito et al., 2008), magnetic shielding of different surface regions (Hartle and Killen, 2006; Wieser et al., 2010; Saito et al., 2010), and production of ions on the lunar surface (Yokota et al., 2009; Tanaka et al., 2009).

The dynamics of the lunar environment is controlled by a complex interaction of multiple physical processes as discussed by Morgan and Shemansky (1991), Hunten and Sprague (1997), Stern (1999), Killen and Ip (1999), Mendillo (2001), Colwell et al. (2007), and Halekas et al. (2010, 2011).

A detailed theoretical study of sodium distribution in the exosphere requires numerical modeling. Having kinetic theory as a physical basis, our exospheric Monte Carlo model preserves the kinetic nature of these exospheric processes. The distinctive features of the model include accounting for the lunar rotation and motion along its orbit, the realistic distribution of the sources, a velocity dependence of the g -factor for both resonant scattering and radia-

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tion pressure acceleration, and simulation of the photolytic reactions in the exosphere.

Using our model we have studied the time and altitude variations of sodium in the lunar exosphere and tail. Simulations were performed starting from the lunar surface and extend up to 400 lunar radii in the anti-sunward direction. The paper discusses the relative importance of the source processes in the sodium exosphere, the effect of solar radiation pressure on the structure of the tail, and the gravitational focusing observed behind the Earth. Model results are presented for a set of phase angles accompanied by comparisons with ground-based observations.

2. Sodium in the exosphere of the Moon

Ground-based observations of the lunar exosphere performed at different phases indicate that the sodium density at the subsolar point is close to $n \approx 60 \text{ cm}^{-3}$ (Potter and Morgan, 1988a; Sprague et al., 1992, 1998; Cremonese and Verani, 1997; Morgan and Shemansky, 1991) and varies in altitude with a scale height of 75–120 km (Morgan and Shemansky, 1991).

At such low densities near the surface, the exosphere is surface-bound. This means that collisions can be neglected in the entire exosphere and sodium atoms move ballistically affected only by gravity, solar radiation pressure and interaction with the surface. Since lunar gravity dominates a particle's motion in the vicinity of the surface, the initial energy distribution of ejected particles to a large degree defines the structure of the exosphere.

Without collisional coupling the exospheric species cannot reach an equilibrium energy distribution. As a result, exospheric atoms produced by the same source process maintain the energy distribution characteristics of the source.

Early observations of sodium (Potter and Morgan, 1988a,b; Tyler et al., 1988) were made near the surface and dominated by a thermal population. Later ground-based observations of the extended lunar exosphere (Mendillo et al., 1991, 1993) suggested that a more energetic sodium population (Ip, 1991; Flynn and Mendillo, 1995; Smyth and Marconi, 1995) can be created by processes such as photodesorption, solar wind sputtering, or meteoritic impact vaporization. The distinction between those populations is discussed in details by Sprague et al. (1992) and Stern and Flynn (1995).

The initial energy of most neutral sodium atoms injected into the exosphere is not sufficient for gravitational escape from the Moon. Only about 10% of them directly escape from the exosphere. The rest move along trajectories that intersect the lunar surface where they can be scattered back or become bound to the lunar regolith. Depending on the radial component of their heliocentric velocity, neutral sodium atoms can be accelerated in the anti-solar direction by solar radiation pressure, which would allow particles that have speeds close to escape to get additional momenta, and escape the Moon's gravity and start their motion into the sodium tail.

2.1. Source and loss processes of sodium in lunar exosphere

Sodium atoms can be released into the exosphere of the Moon via a rich set of source processes (Morgan and Killen, 1997; Stern, 1999; Morgan and Shemansky, 1991; Sprague et al., 1992; Smyth and Marconi, 1995; Sarantos et al., 2010; McGrath et al., 1986; Cintala, 1992) of which the most important are thermal desorption, photon-stimulated desorption, sputtering by solar wind, and micrometeorite vaporization.

2.1.1. Micrometeorite vaporization

Micrometeorite vaporization has been suggested by Potter and Morgan (1988b) as a source of sodium in the exosphere on the Moon. Later, importance of this source process was studied by Hunten and Sprague (1991) and Hunten et al. (1998) by observing the variation of the lunar exosphere during passage of meteor streams. The effect of this source process on the dynamics of the exosphere has been studied by means of numerical modeling by Cintala (1992), Mangano et al. (2007), Sarantos et al. (2008), and Lee et al. (2011).

The sodium source rate due to micrometeorite vaporization varies in the range $\sim 2\text{--}4.9 \times 10^4 \text{ atoms cm}^{-2} \text{ s}^{-1}$ (Smyth and Marconi, 1995; Morgan and Killen, 1997; Bruno et al., 2006, 2007). Killen et al. (2012) suggest that the source rate is distributed uniformly over the lunar surface and the ejecta can be described by a Maxwellian distribution with a temperature of 3000–5000 K (Sarantos et al., 2010, 2012b). A non-uniform distribution of the source rate with its maximum at the equator is discussed by Cremonese et al. (2013).

It is important to note that the source rate and temperature of meteoritic impact vaporization source are not completely independent: the brightness of the exosphere, I (which is the measurable parameter) is inversely proportional to the square root of the source temperature, T and proportional to the source rate, Φ_{MIV} ,

$$I \propto \Phi_{\text{MIV}} / \sqrt{T}. \quad (1)$$

2.1.2. Sputtering

Bombardment of the lunar surface by energetic solar wind and magnetospheric ions can sputter sodium atoms from lunar regolith into the exosphere. But the primary role of sputtering may be to enhance the diffusion of sodium atoms from deeper layers of regolith to the lunar surface where they can be injected into the exosphere by desorption processes (McGrath et al., 1986; Potter et al., 2000; Johnson and Baragiola, 1991). The details of the sodium production by sputtering is discussed by Wurz et al. (2007) and Barghouty et al. (2011).

The flux of sodium atoms produced directly by sputtering of the surface can be expressed as

$$\Phi_s = Y f_{\text{Na}} \Phi_i, \quad (2)$$

where $f_{\text{Na}} = 0.0053$ is the surface fraction of sodium, Y is the total sputtering yield, and Φ_s and Φ_i are sputtering and incident ion fluxes, respectively (Killen et al., 2007; Mura et al., 2009, 2010; Burger et al., 2010). The sputtering flux can be reformulated in terms of sputtering cross section, σ_s , as $\Phi_s = \sigma_s \Phi_i$. Here, σ is the surface density of sodium. Yakshinskiy and Madey (1999) and Killen et al. (2012) suggest that the surface sodium number density is in the range of $\sigma = (3\text{--}3.9) \times 10^{12} \text{ cm}^{-2}$. Laboratory study of sputtering contribution to the sodium population of the lunar exosphere by Dukes et al. (2011) have shown that the cross-section for sputtering of Na adsorbed on mineral surfaces is $\sigma_s = 10^{-15} \text{ cm}^2 \text{ atoms}^{-1}$ and most of sodium is sputtered as ions.

With the typical values of the sputtering yield by solar wind particles $Y = 0.05$ (Wurz et al., 2007) and precipitating flux of $\Phi_{\text{SW}} = 1\text{--}4 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1}$ (Sarantos et al., 2010, 2012b), the flux of directly sputtered sodium is about $2.65 \times 10^4 \text{ Na cm}^{-2} \text{ s}^{-1}$ at the sub-solar point.

Energy of sputtered sodium atoms does not depend on the local surface temperature and is described by Eq. (3) (Sigmund, 1981; Betz and Wien, 1994)

$$f(E_e) \sim \frac{E_e}{(E_e + E_b)^3} \left[1 - \sqrt{\frac{E_e + E_b}{E_i} \frac{(m_H + m_{\text{Na}})^2}{4m_H m_{\text{Na}}}} \right], \quad (3)$$

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