Solar Wind Sputtering Rates of Small Bodies and Ion Mass Spectrometry Detection of Secondary Ions

M. J. Schaible1, C. A. Dukes1, A. C. Hutcherson2, P. Lee3,4,5, M. R. Collier6, and R. E. Johnson1,2

1 Engineering Physics Program, University of Virginia, Charlottesville, VA, USA, 2 Astronomy Department, University of Virginia, Charlottesville, VA, USA, 3 SETI Institute, Mountain View, CA, USA, 4 NASA Ames Research Center, Mountain View, CA, USA, 5 Mars Institute, Mountain View, CA, USA, 6 NASA Goddard Space Flight Center, Greenbelt, MD, USA

Abstract  Solar wind interactions with the surfaces of asteroids and small moons eject atoms and molecules from the uppermost several nanometers of regolith grains through a process called sputtering. A small fraction of the sputtered species, called secondary ions, leave the surface in an ionized state, and these are diagnostic of the surface composition. Detection of secondary ions using ion mass spectrometry (IMS) provides a powerful method of analysis due to low backgrounds and high instrument sensitivities. However, the sputtered secondary ion yield and the atomic composition of the surface are not 1-to-1 correlated. Thus, relative yield fractions based on experimental measurements are needed to convert measured spectra to surface composition. Here available experimental results are combined with computationally derived solar wind sputtering yields to estimate secondary ion fluxes from asteroid-sized bodies in the solar system. The Monte Carlo simulation code SDTrimSP is used to estimate the total sputtering yield due to solar wind ion bombardment for a diverse suite of meteorite and lunar soil compositions. Experimentally measured relative secondary ion yields are analyzed to determine the abundance of refractory species (Mg+, Al+, Ca++, and Fe++) relative to Si+, and it is shown that relative abundances indicate whether a body is primitive or has undergone significant geologic reprocessing. Finally, estimates of the sputtered secondary ion fluxes are used to determine the IMS sensitivity required to adequately resolve major element ratios for nominal orbital geometries.

Plain Language Summary  Determining the precise atomic composition of airless bodies in the solar system can only be carried out by returning samples to Earth, landing on the surface, or sampling the atmosphere. Solar wind plasma ejects atoms and ions from the surfaces of airless bodies, and these ions can be detected with high sensitivity using ion mass spectrometry. Using combined experimental and computational results, we present a model that can be used to estimate the rate at which ions are ejected from the surfaces of airless bodies and show that such ejected ions can be easily detected using mass spectrometry techniques. Furthermore, it is shown that analysis of the relative amounts of sputtered refractory species such as Fe, Si, and Mg can be used to constrain the geologic history of such bodies. We conclude that including an ion mass spectrometer on a spacecraft mission will allow the composition of the uppermost surface to be determined and will also provide information on the likely environment in which the body formed. Such information could prove immensely valuable in determining the history of bodies in our solar system and the availability of resources in our solar neighborhood.

1. Introduction

Throughout their history, airless bodies in the solar system are exposed to ambient gases, plasma, and impacts which modify the regolith composition, topography, grain morphology, and charge state of the uppermost grains. Energetic impacts eject surface material, thereby creating a collisionless atmosphere, called an exosphere, such as those surrounding Mercury, the asteroids, and most moons. Detection and analysis of an exosphere can be used to determine the surface composition of airless bodies and may provide information about their geologic past. Additionally, understanding the compositional distribution of bodies in near-Earth and outer solar system orbits provides clues to the origin and loss of volatile species and complex organic molecules on Earth (Alexander et al., 2012), as well as the availability of valuable resources in our solar neighborhood.
Material can be ejected from surfaces in space by incident solar wind and magnetospheric plasmas, micrometeorites, and UV photons (Johnson, 2002; Madey et al., 2002). When the gravitational potential of a body is small, ejected particles travel radially outward and become subject to ambient conditions. While photons and electrons can electronically or thermally excite and desorb volatile species from the surfaces (e.g., Madey et al., 1998), impacting ions eject all types of atoms and molecules from the top ~1 nm of grains in a processes known as sputtering. Ions ejected from the surface through sputtering processes are called secondary ions. Here we describe the potential for a spacecraft equipped with a sensitive ion mass spectrometer (IMS) to provide in situ surface compositional analysis through direct detection of ejected secondary ions. Although the sole ejection mechanism considered here is solar wind ion sputtering, other processes such as micrometeorite impacts and photoionization can generate significant fluxes of ions as well and should be incorporated into a complete model of ion density in small body exospheres (Cipriani et al., 2011; Schläppi et al., 2008).

Analyses of meteorites (Nittler et al., 2004) and samples returned by spacecraft missions (Nakashima et al., 2013; Saal et al., 2008) have shown that the chemical composition of samples can provide rich insights into the geologic history of the parent bodies. However, meteoritic samples are potentially biased toward a small number of parent bodies (Burbine et al., 2002; Wasson, 1995), and returned samples are only available for a small number of lunar sites, comet 81P/Wild 2 (Brownlee et al., 2006), and the S-type asteroid Itokawa (Noguchi et al., 2011). Although laboratory analysis of samples provides the ideal means of compositional and mineralogical analysis (Weisberg et al., 2006), sample return from a large number of solar system bodies is costly, time-consuming, and carries significant risk. Furthermore, samples analyzed after exposure to Earth’s atmosphere risk contamination and chemical alteration even under relatively “clean” conditions such as those maintained for the Apollo lunar soil samples (Elsila et al., 2016; Swart et al., 1983). Terrestrial and orbital Earth-based remote observations allow the surfaces of a much larger number of bodies to be studied. However, the information obtained is restricted to optical reflectance and thermal emission for the identification of minerals, ices, and organic species. Additionally, the spectral features of minerals and silicates are typically broad so that only limited compositional information can be obtained. Therefore, a low-cost, compact IMS that could be sent to a large number of inner and outer solar system bodies on a small spacecraft could potentially provide extremely valuable information about the elemental and chemical composition of airless bodies and the availability of useful resources.

Surface-bound exospheres have been observed around our Moon (Benna et al., 2015; Yokota et al., 2009) and Mercury (Burger et al., 2014), Europa (Cassidy et al., 2007; Hall et al., 1995; Johnson et al., 1998), and the icy Saturnian moons (Teolis et al., 2010; Tokar et al., 2012) and are expected around all airless bodies in space given the ubiquitous nature of their formation processes. Recent data from the Lunar Atmosphere and Dust Environment Explorer neutral mass spectrometer (LADEE NMS) (Mahaffy et al., 2014), Cassini Ion and Neutral Mass Spectrometer (Waite et al., 2004), and the Rosetta ROSINA (Altwegg et al., 2012) instruments have shown the capability of mass spectrometry to provide detailed information on the surface composition, volatile transport, and desorption processes on airless bodies. However, these studies primarily focused on detecting neutral gas species which requires relatively high abundances to differentiate species originating on the target body from instrument outgassing. Additionally, neutral mass spectrometers (NMS) require that collected species be ionized prior to analysis, thus complicating the compositional analysis. These characteristics make NMS detection of refractories challenging, although small signals have been seen for a few species after long-term monitoring (Wurz et al., 2015). Secondary ion mass spectrometry has long been proposed as an in situ technique for determining the atomic composition of airless body surfaces (Elphic et al., 1991; Johnson & Baragiola, 1991). Numerous laboratory experiments have shown that low-energy (typically ~1–50 eV) secondary ions ejected during 1–100 keV H+ and He+ bombardment of silicates can be directly analyzed using IMS without the need for an additional ionization step typical for neutral mass spectrometers. Furthermore, IMS instruments benefit from high sensitivity to ions which can be extracted and focused, coupled with low backgrounds from the instrument, spacecraft, and ambient plasma. Therefore, IMS represents a potentially powerful tool to determine the surface composition of airless bodies and constrain the geologic history of objects throughout our solar system.
Secondary ion yields (ejected ions per incident ion) typically make up only a small fraction of the total sputtering yield (total ejected species per incident ion), and for typical oxides the ion yields are known to depend sensitively on the atomic fraction of oxygen on the surface (Franzreb et al., 2004). Thus, the surface chemistry and possibly the bonding structure (i.e., crystalline versus amorphous) of the target material will affect the relative abundance of ejected ions. In addition, relative ion fractions have a roughly exponential dependence on the ionization energy (Elphic et al., 1991). The total flux of secondary ions detected by an instrument will depend on the incident plasma, photon, and meteorite fluxes, as well as the spacecraft altitude, time-of-day, and local surface topography. Ejected ions are influenced by local and solar electromagnetic fields, but, for spacecraft orbital altitudes less than the gyroradius of the ions, trajectories can be traced back to a point of origin on the surface such that compositional mapping is possible. If ions are detected sufficiently close to the surface of a body the detected ion spectra depend primarily on the chemical and structural makeup of the uppermost surface. The technique suggested here is not meant to replace other surficial composition instruments, such as X-ray and gamma ray spectrometers, but rather, when present together, can compliment such instruments as these all sample different depths of the regolith. In the absence of spectrometers, IMS can still provide useful surface information.

The goal of this work is to estimate the ejected secondary ion flux from the surface of asteroids or small moons due to solar wind sputtering and to analyze the potential for a spacecraft IMS to adequately determine the major element composition for nominal orbital geometries. First, we show that the Monte Carlo code SDTrimSP (Mutzke et al., 2011) is able to reproduce experimental sputtering yields from simple oxide materials for 0.5–10 keV incident ions, as well as the depletion of oxygen from the surface due to preferential sputtering. For both simple oxides and complex meteorite compositions, SDTrimSP reproduces stoichiometric yields at high incident ion fluences as expected by comparison with laboratory sputtering measurements (Behrisch & Eckstein, 2007). Secondary ion spectra measurements from lunar soils are used to determine relative yields which are necessary to correlate measured secondary ion spectra with surface composition. Using standard meteorite classifications as guidance, it is shown that secondary ion spectra can be used to distinguish bodies as primitive versus evolved. By combining the elemental yield estimates from SDTrimSP with the relative yields and quantitative measurements of the secondary ion yield for Si$^+$, total secondary ion yields for the primary refractory species (Mg$^+$, Al$^+$, Ca$^+$, and Fe$^+$) are estimated. Finally, the secondary ion yields are used to roughly estimate the instrument sensitivity and orbital duration required to obtain sufficient counting statistics and accurately determine the composition of an airless body.

2. Solar Wind Sputtering

Despite a long and rich history of sputtering studies in radiation physics and an interest in such results by the space science community, the bulk of ion bombardment data and theoretical considerations have focused on sputtering of metals, usually by heavy ions. Sputtering yield measurements for oxides and minerals with solar wind energy H$^+$ and He$^{++}$ is sparse. Monte Carlo programs are often used to estimate solar wind sputtering yields although results can be inaccurate at the low energies (below 10 keV) (Wittmaack, 2004) which comprise the largest abundance at average solar wind conditions. Furthermore, a static surface composition is often assumed even though it is known that composition changes as a function of irradiation fluence. However, experiments at solar wind energies (~1 keV/amu) have been carried out giving the total sputtering yields for several simple oxides (Hijazi et al., 2014; Roth et al., 1979) as well as the relative secondary ion yields from a small number of Apollo lunar soils (Dukes & Baragiola, 2015; Schaible, 2014) and soil simulants (Elphic et al., 1991; Meyer et al., 2011), thus allowing for some comparison with computational results.

When multicomponent materials, such as oxides, are exposed to charged particle radiation, preferential ejection of species with lower surface binding energies such as oxygen and sodium can lead to an evolving surface composition. For surfaces of more complex silicates containing multiple refractory elements (e.g., Mg and Fe), preferential sputtering results in an enrichment in certain elements and depletion in others. Material can also leave the surface as molecular species as has been shown most dramatically in water ice for which H$_2$O, O$_2$, and H$_2$ are the dominant ejecta (Brown & Johnson, 1986). Similarly, SiO$^-$ and Si$_2^-$ have been detected as sputter products from SiO$_2$ (Maul & Wittmaack, 1975), and oxide ions such as NaO$^-$ and MgO$^+$ are seen in the secondary ion spectra of lunar soils and simulants (Dukes & Baragiola, 2015; Elphic et al., 1991; Schaible, 2014). Barghouty et al. (2011) simulated solar wind erosion of lunar KREEP (potassium, rare earth elements, and phosphorus) soil using the popular Monte Carlo program SRIM (Ziegler et al., 2008). They found that including
sputtering contributions from heavier solar wind ions (e.g., O$_{6-8}^+$ and C$_{4-6}^+$) in addition to H$^+$ and He$_{2+}$ increased the total sputter yield 26%. Calculating the change in the surface composition using the model of Starukhina (2003), they showed that the atomic abundance of O and other weakly bound elements decreased by as much as ~40%, while strongly bound species such as Si and Ti were enhanced by as much as 80% relative to their initial abundances (Barghouty et al., 2011). Steady state conditions were reached after timescales of ~10$^3$ years assuming an incident ion fluence of ~10$^8$ ion cm$^{-2}$ s$^{-1}$, corresponding to fluences of ~10$^{19}$ cm$^{-2}$.

Including the additional effects of potential sputtering due to the interaction of multiply charged incident ions with a surface led to an additional 26% enhancement in the total yield and more pronounced surface compositional change (Barghouty et al., 2011). Meyer et al. (2011) measured the effects of potential sputtering for multiply charged Ar ions and reported a 50% increase for Ar$_{6+}$ and a factor of 2 enhancement for Ar$_{9+}$ in the oxygen sputtering yield over singly charged Ar$^+$ incident on lunar soil simulants. Compared to H$^+$, this corresponds to an 80 times greater yield for Ar$_{6+}$ and a 160 times greater yield for Ar$_{9+}$. Granular regoliths were studied computationally by Cassidy and Johnson (2005), and it was found that shadowing could cause the total yield to decrease by a factor of ~3.

Variation in sputtering yield with fluence has been identified through X-ray photoelectron spectroscopy (XPS) measurements of surface compositional changes in silicates, troilite, and plagioclase due to solar wind-type ion irradiation (Dukes et al., 2011; Loeffler et al., 2009). For example, 4 keV He$^+$ ion bombardment of olivine is seen to cause chemical reduction and metalization of the surface (Dukes et al., 1999; Loeffler et al., 2009). Formation of nanophase Fe, concurrent with sputter removal of oxygen, has been suggested to account for visible reddening and darkening observed in lunar soil and S-type asteroids (Hapke, 2001; Loeffler et al., 2009; Pieters et al., 1993). Using XPS, Dukes and Baragiola (2015) measured oxygen decreases of ~1 – 5% (atomic percentage) in the surface layers (outermost ~5 nm) for lunar soils after > 4 × 10$^{17}$ He$^+$ cm$^{-2}$ irradiation, corresponding to a ~5 – 20% change in abundance. The observed experimental oxygen decrease is somewhat less than that predicted by Barghouty et al. (2011), which can be explained by the roughness of the granular soil and the geometry of the experiments. The final oxidation state of the surface is of interest as it may have implications for understanding the origins of protoplanetary silicate grains and their catalytic effects on chemical reactions of volatile molecules such as H$_2$O and CO$_2$ (Gontareva et al., 2009).

2.1. Total Sputtering Yields

The total yield, $Y_{\text{tot}}$, for all species ejected through the sputtering process is defined as the total number of atoms and molecules ejected per incident solar wind ion. The total elemental yield, $Y_i$, is the number of atoms (molecules) of species $i$ ejected per incident ion. In the absence of experimental data, estimates of solar wind sputtering yields from surfaces in space are often obtained using SRIM (Poppe & Curry, 2014; Wurz et al., 2007) or by assuming “reasonable” values for $Y_{\text{tot}}$ and stoichiometric yield ratios based on a representative bulk composition (Cipriani et al., 2011). Although SRIM has been shown to be useful for calculating net yields, penetration depths, and sputtered atom energy distributions for metals at incident ion energies above ~10 keV (Ziegler et al., 2008), results are less certain for oxides and minerals where cohesive energies and bond strengths depend on the composition and structure of the solid and the elemental abundance does not remain constant. Additionally, at typical solar wind energies (~0.5 – 10 keV), SRIM has been shown to give inaccurate results even for metals (Wittmaack, 2004). A more recently developed program, SDTrimSP (Mutzke et al., 2011), available through an academic agreement with the Max-Planck-Institut für Plasmaphysik, has been shown to more accurately reproduce sputtering yields for metals and oxides at low incident ion energies (Hofsäss et al., 2014). In addition, SDTrimSP dynamically updates the target surface composition to account for preferential sputtering, and more sophisticated applications can account for the reemission of implanted atoms through diffusion (Mutzke et al., 2011). However, neither the SRIM nor SDTrimSP programs are able to account for material crystallinity, chemical effects, or surface topography which influences comparisons with experiment as discussed below.

2.1.1. Oxide Sputtering Yields

A principal parameter in determining $Y_i$ for a given surface constituent is the surface binding energy, $E_i^S$, defined as the energy needed to remove an atom of species $i$ from the surface in vacuum. Published sputtering yield estimates often use $E_i^S$ values derived from the sublimation enthalpy for the elemental solid (e.g., $E_i^S = \Delta H_i^\text{s}$) (Barghouty et al., 2011; Poppe & Curry, 2014; Wurz et al., 2007). However, $E_i^S$ in oxides may vary significantly from elemental solids as it depends on the local bonding environment in the outermost atomic layers. Several efforts have been made to account for the crystal phase and composition of mineral targets based on various combinations of the enthalpy of sublimation $\Delta H_i^\text{s}$, the enthalpy of formation $\Delta H_i^f$,
Figure 1. Total yields obtained from laboratory irradiation experiments of (a and c) SiO₂ and (b and d) Al₂O₃ by 0.1–10 keV H⁺ and He⁺ ions. Yields calculated by SRIM and SDTrimSP are also shown, and descriptions of the surface binding energy models and experimental data sets indicated in the legend are given in the text.

and the enthalpy of dissociation $\Delta H^D$ for gas species (e.g., May et al., 2000). SDTrimSP incorporates several different surface binding models appropriate for different target types (Mutzke et al., 2011). The simplest of these, which is the same as that used in SRIM, specifies $E_S^i$ independently for each elemental species and maintains it as a constant regardless of the surface composition.

Figure 1 gives the total sputtering yield for several simple oxide targets as a function of incident ion energy obtained using both the SRIM and SDTrimSP simulation codes. The SRIM simulations were run using both the default $E_S^i$ values and modified values obtained by first calculating the total heat of atomization for the oxide, for example, $\Delta H_{\text{SiO}_2}^f + \Delta H_{\text{Si}}^s + \Delta H_{\text{O}_2}^s$, and then normalizing $E_S^i$ of the metal species with respect to Si following

$$E_S^i = \frac{\Delta H_f^i}{\Delta H_{\text{Si}}^s} \frac{1}{n} \left[ \Delta H_f^s + \sum_i \left( \Delta H_{\text{solid}}^i + \Delta H_{\text{gas}}^i \right) \right]$$  \hspace{1cm} (1)

where $n$ is the number of atoms in a stoichiometric unit of compound $X$ and the summation is over all elements in the compound which exist elementally in either the solid or gas phases (May et al., 2000). Equation (1) was used only for the SRIM simulations. In the SDTrimSP simulations presented here, refractory species were assumed to have surface binding energies equal to the elemental sublimation enthalpy, $E_S^i = \Delta H_f^i$ (e.g., Si(s) $\rightarrow$ Si(g)), while for oxygen $E_S^O$ was varied between 1 and 3 eV. Although SDTrimSP provides several different methods for determining $E_S^i$, the various models did not improve agreement with the experimental data. Over 75,000 incident ions were simulated in both programs.

The computational yields in Figure 1 are compared to total sputtering yield measurements for simple oxides determined using large incident ion beam fluxes and removal of micrograms of material (Roth et al., 1979; Wehner & KenKnight, 1967). The Wehner and KenKnight (1967) total sputtering yields were obtained using hydrogen and helium mass-analyzed ion beams to drill holes through thin oxide foils. These yields were estimated to be uncertain by at least ~20% for Al₂O₃ and >50% for SiO₂ (Wehner & KenKnight, 1967). The Roth et al. (1979) data were taken using a 1–15 kV, mass-analyzed ion accelerator, and samples were irradiated at fluxes of $\sim 10^{15}$ ions/cm²/s, ~10² times larger than solar wind fluxes at 1 AU, to fluences of $>10^{19}$ cm⁻². Total yield measurements in Roth et al. (1979) were determined through weight loss measurements of the sample with a sensitivity of < 1 µg (Bay et al., 1977). Unfortunately, a full analysis of experimental uncertainty is not available for the Roth et al. (1979) data shown, but experiments performed on metals suggest at least a 10% uncertainty (Bay et al., 1977). Due to repeatability error and responsivity of the microbalance when measuring
such low yields, as well as fluctuations in the beam current, and nonuniform beam fluxes over the irradiated area, the experimental uncertainties may be larger. The variance in the SRIM and SDTrimSP yields are much smaller, of the same order as the size of the data markers.

It is well known that SRIM agrees well with experimental measurements for elemental metal yields at incident ion energies $E_{\text{inc}}$ greater than $\sim 10$ keV (Ziegler et al., 2008). This is because a larger portion of the incident ion energy is deposited in the bulk of the material. However, even after accounting for increased $E^2$ in minerals, SRIM consistently overestimated the experimental total sputtering yields by a factor of 2–3 at solar wind energies. This disagreement stems, at least in part, from the inability of SRIM to account for depletion of elements with low $E^2$ from the surface. Therefore, the SRIM program does not give a good match to the experimental data at solar wind energies and should not be used to estimate solar wind sputtering rates from rocky bodies. SDTrimSP matches the experimental data for both H\(^+\) and He\(^+\) bombardment of SiO\(_2\) and Al\(_2\)O\(_3\) to within $\sim 50\%$ or better at solar wind energies and provides a much better estimate of solar wind sputtering yields than SRIM. Thus, we use SDTrimSP to determine the total and elemental yields for a wide range of lunar soil and meteorite compositions as described further below. Although experimentally measured elemental yields are not readily available for complex regolith grains, it is reasonable to expect that the energy loss processes are largely similar to those in simple oxides and that the elemental yields can be roughly reproduced by computational methods.

### 2.1.2. Depletion of Surficial Oxygen

Changes in surface composition caused by preferential sputtering can be roughly accounted for using the SDTrimSP program (Hofsäss et al., 2014; von Toussaint et al., 2016). The target composition is updated every $\sim 500$ incident ions, and composition is independently tracked in $\sim 1$ nm thick sections throughout the depth of the sample. For this work, the thickness of the target material (500 nm) is much greater than the penetration depth of keV ions ($\sim 10–30$ nm). The incident H\(^+\) and He\(^+\) ions were no longer tracked after their energy had dropped below the minimum displacement energy of the solid such that there was no accumulation of implanted particles. Although accumulation of incident ions can lead to density changes in the implanted regions, both H and He are small and can rapidly diffuse through the bulk so that neglecting accumulation in the simulations is expected to have only a small effect.

The total and elemental sputtering yields plotted as a function of fluence are shown in Figure 2 for 1 keV H\(^+\) and 4 keV He\(^+\) bombardment of SiO\(_2\) and Al\(_2\)O\(_3\). It is seen that for increasing irradiation fluences the oxygen yield decreases while the yields for Si and Al increase. This is due to depletion of oxygen from the surface and an enrichment in Si or Al, respectively. This result qualitatively agrees with experimental measurements on minerals, glasses, and lunar soil (Dukes & Baragiola, 2015; Dukes et al., 1999; Loeffler et al., 2009). An approximate equilibrium state is reached at fluences of $\sim 10^{19}$ cm\(^{-2}\) after which point the yields are roughly stoichiometric with the bulk composition. Both experiments and simulations considered fluences of $\sim 10^{19}$ cm\(^{-2}\), corresponding to solar wind H\(^+\) exposure time of $\sim 10^2$ years assuming a solar wind flux of $\sim 10^8$ cm\(^{-2}\) s\(^{-1}\) at 1 AU. This timescale implies that yields will be approximately stoichiometric for the majority of inner solar system bodies.

### 2.2. Ion Yields

When silicates are bombarded by solar wind or magnetospheric ions, material is typically ejected in decreasing abundance as (a) neutral atoms, (b) ions, and (c) molecules/clusters. The secondary ion component of the ejected material can be energy selected and analyzed by IMS instruments with high sensitivity and low background (Yokota et al., 2009), thereby providing an accurate means of determining the surface composition. An example of the type of compositional information carried by secondary ions during solar wind-type irradiation of lunar soils is shown in Figure 3. The measurements are normalized to Si to compare spectra obtained under different experimental conditions; total count rates for a unit mass range measured using standard laboratory IMS instruments are typically on the order of $10^5$ s\(^{-1}\). Assuming the same instrumental effective area and crudely extrapolating to solar wind fluxes at 1 AU and spacecraft altitudes of 40 km implies that secondary ion count rates of $\sim 1$ s\(^{-1}\) can be obtained during solar wind bombardment of airless bodies. A more detailed estimate of instrument count rates is given in section 4.

#### 2.2.1. Relative Ion Yields

While the elemental sputtering yield, $Y_i$, depends primarily on the atomic surface abundance, $C_i$, and surface binding energy, $E_i^0$, the elemental secondary ion yield, $Y_i^+$, additionally depends on ionization potential...
Figure 2. Total and individual element sputtering yields as a function of incident ion fluence obtained from SDTrimSP simulations. (a) H\(^+\) and (b) He\(^+\) irradiation of SiO\(_2\); (c and d) irradiation of Al\(_2\)O\(_3\). The yields are approximately stoichiometric after a fluence of \(\sim 10^{19}\) ions/cm\(^2\). The Si elemental yield, \(Y_{Si}\), for SiO\(_2\) is on the order of 0.01 Si per incident H\(^+\), and 0.05 Si per incident He\(^+\).

of the sputtered species. The ionization probability, \(\alpha_i = Y_i^+/Y_i\), can be determined by measuring the intensity of the secondary ion flux with respect to the total flux of ejected material. However, obtaining absolute values of \(\alpha_i\) for each element in a complex, multicomponent material is difficult. Therefore, we define relative elemental ion yields with respect to Si which, due to its presence in roughly equal amounts in all meteorite types, serves as a convenient fiducial. The relative ion yield is defined as

\[
R_i = \frac{Y_i^+}{Y_i^{Si}} C_i \tag{2}
\]

Figure 3. Representative secondary ion spectra normalized to \(^{28}\)Si for approximately keV H\(^+\) and He\(^+\) irradiation of lunar soils (Dukes & Baragiola, 2015; Schaible, 2014) and soil simulants (Elphic et al., 1991). Multiple isotopic and oxide peaks are present in the Schaible and Dukes data, though some of these overlap with the elemental peaks and can be difficult to distinguish clearly. The sensitivity of the Elphic experiments was insufficient to detect many of these peaks.
Figure 4. Relative secondary ion yields calculated for the lunar soil compositions given in Table 1 (65901, 62231, and 10084) (Dukes & Baragiola, 2015; Schaible, 2014) using 2 keV H$^+$ and 4 keV He$^+$ incident ions. The relative yields show a roughly exponential dependence on the elemental ionization energy. Results from Elphic et al. (1991) using lunar soil simulants are also shown, and the values for each of the incident ions listed are averaged for three Apollo soil analogs (10899, 15999, and 69999) such that only limited compositional effects are taken into account. The average calculated using the Schaible (2014) and Dukes and Baragiola (2015) data for actual lunar soils and solar wind energy ions is used in calculations below, and the error bars represent the 1σ variance in the calculated relative yields. Oxygen is not shown since it sputters primarily as a negative ion and thus is not easily measured simultaneously with the positively charged metal ions.

where, as discussed above, at high fluences the ratio of elemental yields $Y_{Si}/Y_{i} \approx C_{Si}/C_{i}$ is a constant determined by the bulk composition.

The relative ion yields calculated from secondary ion measurements of lunar soils and analog targets and for numerous incident ion types and energies are shown in Figure 4, plotted against element ionization energy, $E_{IE}$. Although there are large uncertainties in the $R_{i}$ determined from experimental SIMS spectra, a roughly exponential decrease is seen in the relative yield with increasing ionization energy. However, there appears to be a plateau between Ca$^+$ and Mg$^+$ that does not follow the exponential trend, although the error bars are large. The higher than expected and relatively constant yields in this range are currently unexplained, and further experiments are needed to determine if the plateau is real.

The atomic abundance of the major elements for the lunar soil samples considered are given in Table 1. Soils LS65901 and LS62231 are mature highland samples (<1 mm grain sizes) of similar composition, while LS10084 is a mature mare soil. The values for bulk composition were taken from the lunar sample compendium (curator.jsc.nasa.gov/lunar/lsc/), and atomic abundances at the surface were derived from XPS measurements for unirradiated samples (Dukes & Baragiola, 2015; Housley, 1992). The elemental yields determined by SDTrimSP for solar wind composition (95% 1 keV H$^+$ + 5% 4 keV He$^+$) ion irradiation are given for fluences greater than $10^{19}$ cm$^{-2}$. Since at irradiation fluences of $\sim 10^{19}$ cm$^{-2}$ only $\sim$5 nm of surface material are removed, approximately the depth of sensitivity for the XPS measurements, and since the bulk compositions are averages for the lunar samples and not necessarily representative of any single sample, the XPS compositions are used as the initial composition for the SDTrimSP simulations.

Standard laboratory IMS techniques can easily separate mass to charge ratios of order unity, as seen in Figure 3, and thus, relative abundances of the isotopic ratios can in principle be determined. However, the compositions in Table 1 do not distinguish the isotopic fractions, and therefore, it is necessary to account for the relative isotope abundances when deriving $R_{i}$ from the experimental SIMS spectra. Isotopic abundance corrections were done by taking the SIMS intensity of the most abundant isotopic mass for each element, determined by integrating the total counts over a single mass unit, and dividing by the average solar system isotopic abundance (de Laeter et al., 2003).
Table 1
Compositions Ci, Given in Atomic Fraction for Apollo 16 and Apollo 11 Mature Lunar Soil Samples for Which Secondary Ion Spectra Have Been Collected

<table>
<thead>
<tr>
<th></th>
<th>LS65901 Mature Highland Soil</th>
<th>LS62231 Mature Highland Soil</th>
<th>LS10084 Mature Mare Soil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bulk (at. %)</td>
<td>XPS (at. %)</td>
<td>Yi (atom/ion)</td>
</tr>
<tr>
<td>Na</td>
<td>0.16</td>
<td>0.16</td>
<td>0.0001</td>
</tr>
<tr>
<td>Mg</td>
<td>3.21</td>
<td>2.10</td>
<td>0.0007</td>
</tr>
<tr>
<td>Al</td>
<td>5.42</td>
<td>9.40</td>
<td>0.0032</td>
</tr>
<tr>
<td>Si</td>
<td>15.70</td>
<td>18.50</td>
<td>0.0063</td>
</tr>
<tr>
<td>K</td>
<td>0.02</td>
<td>&lt;0.0001</td>
<td>0.03</td>
</tr>
<tr>
<td>Ca</td>
<td>5.58</td>
<td>5.30</td>
<td>0.0018</td>
</tr>
<tr>
<td>Ti</td>
<td>0.16</td>
<td>0.16</td>
<td>0.0001</td>
</tr>
<tr>
<td>Mn</td>
<td>0.02</td>
<td>&lt;0.0001</td>
<td>0.03</td>
</tr>
<tr>
<td>Fe</td>
<td>1.68</td>
<td>3.10</td>
<td>0.0011</td>
</tr>
<tr>
<td>O</td>
<td>68.06</td>
<td>61.24</td>
<td>0.0209</td>
</tr>
</tbody>
</table>

Note: Bulk sample compositions were taken from the lunar sample compendium, and the XPS compositions representative of the uppermost several monolayers were taken from Housley (1992) for LS65901, and from Dukes and Baragiola (2015) for LS62231 and LS10084. The elemental yields Yi were determined from SDTrimSP calculations and are given for solar wind composition incident ions. The elemental yields determined by SDTrimSP are approximately stoichiometric for high fluences (>10^19 cm^−2). The total yields and estimated secondary ion yields are given in the bottom two rows.

2.2.2. Sputtered Ion Yield Estimates
The average relative ion yield, < R_i >, and variance for solar wind ion radiation of lunar soils, measured using the experimental system described in Dukes and Baragiola (2015), are given in Table 2. Using the elemental sputtering yield obtained from SDTrimSP, Yi, and noting that it can be shown that α_i = < R_i > α_{Si}, the elemental ion yield is given here as

Y_i^+ = Y_i < R_i > α_{Si} (3)

and the ratio of the secondary ion sputtering yields to Si^+ is

Y_{Si}^+ / Y_{Si}^+ = Y_i < R_i > . (4)

The ratio of the secondary ion sputtering yields for LS62231 relative to Si^+ determined from experimental measurements (Dukes & Baragiola, 2015) and using equation (4) are shown in the final two columns of Table 2. It is seen that the computational methods agree with the measurements for most elements to within the uncertainties.

The relative yields in Figure 4 indicate that secondary ion yields depend weakly on the type or energy of the incident ion used and on the concentration of oxygen in the surface layer which is depleted with increasing fluence as discussed above. When targets containing Si are bombarded by ∼10 keV Ar^+, the fraction of Si atoms leaving the surface as ions is at least α_{Si} ∼ 0.2 for SiO_4 and for 40% O in the surface layer α_{Si} ∼ 0.01 (Franzreb et al., 2004). For pure Si, α_{Si} drops to ∼10^{-4}. However, these measurements are “useful” ion yields and accounted for only the detected Si^+ ions sputtered per incident ion. Sputtered secondary ions that did not reach the detector were not included in the useful yield determination, and therefore, the actual ionization probabilities could be somewhat higher.

It is important to note that incident H^+ can chemically react with the target material, and experiments seem to indicate that hydrogen reactions with oxide targets may affect both total and secondary ion yields. A comparison of the total secondary ion counts, integrated over all masses for lunar soils irradiated with 1 – 10 keV H^+, He^+, and noble gas ions, indicate ion yields for incident hydrogen are almost an order of magnitude larger...
than expected based on extrapolations of the total yield versus nuclear stopping cross section (Elphic et al., 1991; Schaible, 2014). The importance of hydrogen chemistry was demonstrated in Schaible and Baragiola (2011) and the remaining yields were determined using equation (3) and the average relative yields for a given compositional type (e.g., lunar or chondritic) to make accurate predictions of trace species such as Mn are often preferred in the lab setting, limited instrument sensitivity and background sources make meeting the required detection limits for these trace elements much more difficult in space. The use of readily detected refractory metal ions for which background sources are negligible represents a more robust method to identify composition and carry out parent body classification.

3. Determination of Small Body Classification

It has previously been shown that the ratios of certain refractory elements can be used to discriminate between some meteorite classes (Nittler et al., 2004). Although oxygen isotope measurements or measurements of trace species such as Mn are often preferred in the lab setting, limited instrument sensitivity and background sources make meeting the required detection limits for these trace elements much more difficult in space. The use of readily detected refractory metal ions for which background sources are negligible represents a more robust method to identify composition and carry out parent body classification.

Using published bulk compositions for the suite of meteorites listed in Table 3, the $Y_i$ were determined using SDTrimSP assuming normally incident solar wind composition ions. Several of the published meteorite compositions (e.g., carbonaceous chondrites) contained a small amount of structurally bound nonrefractory species such as hydrogen, carbon, and nitrogen, in addition to oxygen. Since hydrogen and nitrogen make up only a small atomic percentage of the total composition, these were neglected from the simulated compositions. For target compositions containing carbon, $E_i^+ = 7.37$ eV was used. The remaining SDTrimSP target and incident ion settings used in the lunar soil and meteorite composition simulations were the same as those used to obtain the best match to experimental data for simple oxides discussed in section 2.1.

The average elemental secondary ion yields for the meteorites listed in Table 3 are compared in Figure 5a for Mg, Al, Si, Ca, and Fe. The secondary ion yield for Si$^+$ was derived using the elemental yields determined from the SDTrimSP simulations and taking a conservative ionization fraction for silicon of $\alpha_{Si} = 0.01$, and the remaining yields were determined using equation (3) and the average relative yields given
Table 3  
Meteorite Types and Sample Compositions Considered

<table>
<thead>
<tr>
<th>Martian</th>
<th>HED</th>
<th>Urelites</th>
<th>Carbonaceous chondrites</th>
<th>Enstatite + ordinary chondrites</th>
<th>Aubrites</th>
</tr>
</thead>
<tbody>
<tr>
<td>EETA79001 A</td>
<td>Sioux County</td>
<td>ALHA84136</td>
<td>CM</td>
<td>EL</td>
<td>Bishopville</td>
</tr>
<tr>
<td>EETA79001 B</td>
<td>Serra de Magé</td>
<td>ALHA77257</td>
<td>CV</td>
<td>EH</td>
<td>Bustee</td>
</tr>
<tr>
<td>Shergotty</td>
<td>Y-791195</td>
<td>North Haig</td>
<td>CO</td>
<td>L</td>
<td>Khor Temiki</td>
</tr>
<tr>
<td>ALH 84001</td>
<td>Johnstown</td>
<td>Dingo Pup</td>
<td>CK</td>
<td>LL</td>
<td>Mayo Belwa</td>
</tr>
<tr>
<td>Nakhl</td>
<td>Bholghi</td>
<td>Donga</td>
<td>CR</td>
<td>A</td>
<td>Norton County</td>
</tr>
<tr>
<td>Chassigny</td>
<td>EET 87503</td>
<td>CH</td>
<td>K</td>
<td>Pena Blanca Sp.</td>
<td></td>
</tr>
<tr>
<td>Adirondack</td>
<td>Bialyostok</td>
<td>CI</td>
<td>H</td>
<td>Shallowater</td>
<td></td>
</tr>
<tr>
<td>Humphrey</td>
<td>Petersburg</td>
<td>R</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mazatztal Brook</td>
<td>Haraiya</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALHA77005</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Y_{\text{tot}} = 0.0324$</td>
<td>0.0322</td>
<td>0.0341</td>
<td>0.032</td>
<td>0.0304</td>
<td>0.037</td>
</tr>
<tr>
<td>$Y^+ = 4.65\times10^{-4}$</td>
<td>4.38e$-$4</td>
<td>6.3e$-$4</td>
<td>4.76e$-$4</td>
<td>4.97e$-$4</td>
<td>6.56e$-$4</td>
</tr>
</tbody>
</table>


The average total and secondary ion yields for each meteorite class are given in the bottom two rows.

in Table 2. The error bars represent the variance within a given meteorite class. Additionally, because the $Si^+$ yields are similar for all meteorite types considered, the ratios of the secondary ions yields to the $Si^+$ ion yield, calculated using equation (4), are given in Figure 5b. However, contamination from CO, also at mass = 28 amu, such as would be expected on the surface of Phobos due to deposition during passage through the Mars plasma wake, may complicate signal interpretation. One means of alleviating this concern is to use an IMS with sufficient mass resolution to distinguish the small nuclear mass differences. Alternatively, for bodies such as Phobos, which is tidally locked, deposition should occur preferentially on the Mars facing hemisphere, and IMS measurements can be taken when the moon is outside the plasma wake and exposed only to the solar wind to determine the CO background.

Several secondary ion yield ratios, $Y^+/Y_{Si^+}$, are given in Figure 6 for each of the individual meteorite compositions where the ellipsoids show the rough grouping of compositionally similar meteorite types. Noting that the lunar, HED (howardite-eucrite-diogenite), and Mars compositions are typical of geologically evolved parent bodies, while the chondrites, urelites and aubrites likely represent more primitive solar system materials, it is seen that the expected secondary ion yield ratios can be used to group the parent bodies according to evolved and primitive types. These results show that in principle, an IMS can determine whether the surface material on an airless body has been heavily altered by heating, devolatilization, and differentiation events, or if it is representative of material from the early solar system.

Figure 5. (a) The average secondary ion yields for the meteorite classes given in Table 3. The average $Si^+$ yield is roughly similar for all meteorite classes, while the $Mg^+$, $Al^+$, $Ca^+$, and $Fe^+$ yields are different for primitive and evolved meteorite types. (b) The secondary ion yields divided by the secondary ion yield of $Si^+$. 

SCHAIBLE ET AL. SOLAR WIND SPUTTERING OF SECONDARY IONS 11
Figure 6. Sputtered ion yield ratios for each of the meteorite types given in Table 3 where each meteorite class is assigned a unique color/symbol marker. Ordinary and enstatite chondrites have been grouped (OCsECs) and carbonaceous chondrites (CCs) are a separate group. The yield ratios indicate that detection of secondary ions can be used to distinguish meteorite classes according to primitive-type and geologically evolved parent bodies.

4. Sputtered Ion Fluxes Near Small Bodies

The sputtered ion flux of a species at the surface of an airless body, $\Phi_i^s$, primarily depends on $\Phi_{SW}$, the solar wind ion flux at the heliocentric distance of interest, and $Y_+^i$, the secondary ion yield for each species determined using equation (3). The equation for the sputtered secondary ion flux at the surface of a small body of radius $r_{sb}$ as a function of solar incidence angle is

$$\Phi_i^s(r_{sb}, \theta') = \Phi_{SW} Y_+^i P \cos^{-1.6} \theta'$$

where $P$ is a reduction factor due to regolith porosity and $\theta'$ is the incident ion angle. Irradiation of flat surfaces at angles away from the local surface normal is typically accompanied by an increase in the sputtering yield, and maximum yield values are reached at $\theta' = 60–80^\circ$ from the local surface normal. The sputtering yield dependence on the incident ion angle is often taken to be $\cos^{-1.6} \theta'$ as in equation (5) (Behrisch & Eckstein, 2007), and integrating over all incident ion angles from 0 to $80^\circ$ yields a factor of $\sim 4$. Although it is well known that the SW dynamic pressure can vary significantly and there can be short periods in which extreme low/high flux SW conditions persist, the estimates below assume average solar wind conditions of $\Phi_{SW} \sim 10^8 \text{ cm}^{-2} \text{ s}^{-1}$ which is appropriate for Mars orbits. Objects orbiting closer to the Sun will experience larger ion fluxes. Taking the average elemental yields for lunar soil from the SDFinSP computations, given in Table 1, and the relative yields from Table 2, and assuming a porosity reduction factor of $P = 1/3$ (Cassidy & Johnson, 2005) and an ionization probability for silicon $\alpha_{Si} = 0.01$ (Franzreb et al., 2004), the total flux of Si$^+$ leaving a regolith at the subsolar point of an airless body in the inner solar system is $\Phi_{Si}^s \sim 10^4 \text{ cm}^{-2} \text{ s}^{-1}$. The sputtered secondary ion fluxes predicted here are consistent with the upper limits of most ions in the lunar exosphere (Sarantos, Hartle, et al., 2012; Sarantos, Killen, et al., 2012; Yokota et al., 2009).

Regolith effects and variations in binding energy can create a distribution of ejection energies ranging from $\sim 1$ to 50 eV with a peak ejection energies of $\sim 10$ eV (Dukes & Baragiola, 2015). This entire distribution of ejection energies yields velocities much greater than the escape velocity of a Phobos ($r_{ph} \sim 10 \text{ km}, v_{es} \sim 10^{-6} \text{ eV/amu}$) or 4-Vesta ($r_\text{es} \sim 250 \text{ km}, v_{es} \sim 10^{-3} \text{ eV/amu}$) sized body. As ions move away from the surface, their trajectories are modified by ambient electric ($E$) and magnetic ($B$) fields and momentum transfer from plasma ions. In particular, an ejected ion initially begins to move in the direction parallel to the $E$ field generated by the plasma motion and bends in a direction perpendicular to the $B$ field, resulting in a cycloidal motion in a plane perpendicular to the local $B$ field. For airless bodies outside of planetary magnetospheres, the $B$ field typically assumed is the interplanetary magnetic field (IMF) carried by the solar wind. Due to the pickup motion generated by the $E$ and $B$ fields and the random orientation of the IMF, at large distances from the surface ions are strongly directed in a small distribution of angles with respect to the subsolar point (Yokota & Saito, 2005). However, if an ion is detected at altitudes less than the gyroradius and before significant deflection by the $E$ field occurs, the origin can in principle be determined as has been done for Dione and Rhea using...
Cassini data (Teolis et al., 2010; Tokar et al., 2012). The scale of the pickup motion for a body embedded in the solar wind plasma can be estimated using the gyroradius for an ejected ion, which is given by

\[ r_{gr} = \frac{m v_{\text{ion}} \sin \theta_{bv}}{q B_{sw}} \]  

(6)

where \( m \) is the ion mass, \( q \) is the ion charge, \( v_{\text{ion}} \) is the ion velocity, and \( \theta_{bv} \) is the angle between the ion velocity and the IMF direction. Noting that the average solar wind velocity, \( v_{sw} \), is much larger than the ion ejection velocity and assuming that \( B \sim 1 \) nT, appropriate for orbital distances of Mars and beyond (Russell et al., 1990), and oriented perpendicular to the solar wind, the gyroradius for an ejected Si\(^+\) ion is \( \sim 1 \times 10^5 \) km. Due to the influence on ion trajectory by the \( E \) and \( B \) fields carried by the solar wind, it is important to have a method of measuring the prevailing \( B \) field direction such as a magnetometer instrument included on the spacecraft.

Ions also gain energy due to the IMF influence depending on the ion ejection velocity and the magnitude of the IMF. Assuming that the ions travel in an approximately straight path from the surface to the spacecraft, the velocity increase at the time of detection is given by

\[ \Delta v = \frac{d_{sc}}{m_i \langle v_i \rangle} \left( q_i B \sqrt{\langle v_i \rangle^2 + v_{sw}^2} \right) \]  

(7)

where \( d_{sc} \) is the spacecraft altitude above a body of radius \( r_{sb} \), and \( \langle v_i \rangle \) is the weighted average velocity of the ejected ion. It is important to note that for surfaces of airless bodies can charge positive due to photoelectron emission caused by solar UV irradiation, and this could further increase the ejection velocity of the secondary ions. The estimated change in energy for an Si\(^+\) ion ejected with an initial energy of \( \sim 10 \) eV and at an altitude of 40 km above the surface is \( \sim 10 \) eV assuming a solar wind velocity of \( v_{sw} \sim 1 \) keV/amu. This implies that the majority of ions within \( \sim 40 \) km of an airless body have energies similar to their ejection energy and are still well within the energy acceptance ranges for most IMS instruments. However, at larger distances where the energy gained by ions is significant, the ion energy may be above the acceptance energy of the detector and the mass resolution capability of the instrument will be reduced. In order for an IMS to carry out compositional mapping of a surface, the orbital altitude must be sufficiently low or the field of view of the instrument very narrow. A instrument with a field of view of \( \pm 10^\circ \) at an altitude of 40 km views an area of \( \sim 14 \) km, of the order of the size of most asteroids and moons except for the very largest. However, a narrow field of view decreases the ion count rates, and therefore, compositional mapping more detailed than broad hemispherical determination would be difficult.

Assuming that the gravitational attraction of the body is negligible, assuming any velocity variations are small, the flux at distance \( r_{sc} = r_{sb} + d_{sc} \) from the body center is given as

\[ \Phi_i^+(r_{sc}) = \Phi_i^+(r_{sb}) F \left( \frac{r_{sb}}{r_{sc}} \right) \]  

(8)

where the factor

\[ F \left( \frac{r_{sb}}{r_{sc}} \right) = \left[ 1 - \left( 1 - \left( \frac{r_{sb}}{r_{sc}} \right)^2 \right)^{1/2} \right] \]

accounts for radial expansion as the sputtered species move away from the surface (Johnson, 1990). Using the surface flux calculated for Si\(^+\) above, the flux at a spacecraft altitude of 40 km above a 20 km diameter body is \( \sim 200 \) cm\(^{-2}\) s\(^{-1}\). The count rate for an IMS instrument depends on the instrument sensitivity, aperture opening, and acceptance angle. A conservative estimate for the mass analyzer effective area of \( \sim 10^{-3} \) cm\(^2\) implies that \( \sim 0.2 \) counts per second for Si\(^+\) will be detected above the subsolar point. However, ions can only be detected on the dayside of the body, and some ejected secondary ions will reimpact the surface and therefore cannot be detected. These effects will reduce the total number of ions detected during an orbit.

Ion measurement error follows Poisson statistics, and the uncertainty in the relative abundance is equal to the square root of the total number of counts. Managadze and Sagdeev (1988) quote a required statistical accuracy of \( \sim 1\% \) (10\(^4\) counts per species) to perform space-based IMS measurements. Figure 7 shows the secondary ion fluxes for average lunar and carbonaceous chondrite compositions at 40 km above a 20 km diameter body exposed to average inner solar system solar wind conditions. For a continuous measurement...
mass spectrometry such as a time-of-flight design, only \( \sim 10^3 \) s or a bit over 1 day is needed to obtain sufficient counting statistics for most elements. Even accounting for flux dropoff away from the subsolar point, sufficient counts are easily achievable over short mission lifetime. Prolonged measurement duration can allow for compositional mapping to be carried out over specific surface regions. Furthermore, if the oxygen content in the uppermost surface is greater than the 40% assumed, or if H\(^+\) ions have a significant enhancement effect on the sputtered ion fraction, the sputtered secondary ion flux could be much higher than estimated here. Thus, it is clear that a sufficiently sensitive IMS can rapidly obtain sufficient compositional information for airless bodies and should be considered for future spacecraft missions to small bodies throughout the inner Solar System.

5. Conclusions

We have shown that the combination of laboratory data and modern ion-solid interaction software can be used to estimate secondary ion yields from small planetary bodies, and that measurements of sputtered secondary ion ratios can be used to characterize the surface composition by ion mass spectroscopy in flyby and orbital missions. Such missions do not require returned samples, thus allowing for low-cost encounters with multiple bodies to better understand their origins. For ambient solar wind conditions, we show that monitoring sputtered ion fluxes over the course of only a few days can provide global abundance estimates with a sensitivity of 1% based on recent advances in ion mass spectrometry instrumentation. Although this scenario had been proposed earlier, the appropriate light-weight, small-scale, focused instrumentation is now available to carry out such surveys. Prolonged measurement of secondary ions, even at altitudes of 40 km, can provide compositional mapping across the surface of a small planetary body. Using published compositions for a large suite of meteoritic classes, we have shown that secondary ion compositional ratios can indicate whether the surface is composed of primitive versus altered material for interesting small solar system bodies such as Phobos and Deimos, the moons of Mars, as well as asteroids, Mercury, etc. The estimates presented here are conservative both in terms of the extrapolations based on available yields and in the assumed solar wind conditions. Because surprising and unpredicted exosphere properties have been seen at other bodies such as the Moon and Mercury, there are compelling reasons for the use of an IMS to characterize the refractory composition of small bodies.

While the usage of SDTRIMSP, rather than TRIM, provides more accurate total yields of ion-induced sputtered atoms, particularly for incident energies \( > 1 \) keV, the analysis of returned data from both neutral and ion orbital mass spectrometers would be enhanced by a dedicated program of ion sputtering experiments on a variety of refractory-containing solar system materials with a range of compositions. Such measurements could then be used to recalibrate the simulation software and further improve agreement between experiment and theory, as well as enhance the predictive powers for models such as those presented here. This work, combined with a continued development of new high-sensitivity instrumentation, will aid in the design of mass spectrometers and their incorporation into spacecraft missions looking to determine the composition of asteroids and small moons (e.g., Lee et al., 2015). The use of such instruments to obtain diagnostic measurements of the ages and origins for a number of bodies can provide a unique tool to help constrain the dynamical history of the solar system and, possibly, the availability of valuable resources.

Acknowledgments

M. J. S. and R. E. J. acknowledge support from the NASA Planetary Geology and Geophysics and the NASA Planetary Atmospheres program. We would like to thank A. Mutzke for helpful discussion on the use of SDTRIMSP and P. Williams for clarifications on the measured silicon ionization probabilities. We would like to thank two anonymous reviewers for their helpful comments in improving the quality of the manuscript. The experimental data used here are available in the cited publications, and the raw data and summarized results of the computational simulations are available at https://github.com/mjschaible/SDTRIMSP.git.

References


https://doi.org/10.1016/0039-6028(75)90300-3


