Icarus 227 (2014) 89–93

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Production of neutral gas by micrometeoroid impacts

A. Collette [a,*], Z. Sternovsky [a,b], M. Horanyi [a,c]

[a] Colorado Center for Lunar Dust and Atmospheric Studies, LASP, University of Colorado at Boulder, Boulder, CO 80309, USA
[b] Aerospace Engineering Sciences, University of Colorado at Boulder, Boulder, CO 80309, USA
[c] Department of Physics, University of Colorado at Boulder, Boulder, CO 80309, USA

ARTICLE INFO

Article history:
Received 21 June 2013
Revised 23 August 2013
Accepted 8 September 2013
Available online 19 September 2013

Keywords:
Moon
Mercury
Impact processes
Interplanetary dust

ABSTRACT

We present the first direct laboratory measurement of vapor produced by simulated micrometeoroid bombardment. New in situ observations from the Mercury Surface, Space Environment, Geochemistry and Ranging (MESSENGER) spacecraft, and the anticipation of results from the Lunar Atmosphere and Dust Environment Explorer (LADEE), have highlighted the uncertainty surrounding the role of micrometeoroid impacts in sustaining planetary exospheres. In a recent series of experiments, the quantity of neutral molecules generated by impacts of simulated micrometeorids of 0.1–1 μm radius was measured using a fast ion gauge, over a speed range of 1–10 km/s. The quantity of neutrals released per unit projectile mass, N/m, is consistent with a power law $N/m = v^{\beta}$ in the projectile speed v, with $\beta \sim 2.4$. At the highest speeds tested, the number of neutrals liberated is equivalent to 5% of the atoms in the projectile; complete vaporization is projected at speeds exceeding 20 km/s.

1. Introduction

Surface-bounded exospheres are characterized by extremely low densities, so low that the species are collisionless. Neutral atoms and molecules follow ballistic trajectories between the surface of the object and space; consequently, the exospheric constituents observed around objects such as the Moon and Mercury are governed by source and loss processes operating at these boundaries (Stern, 1999; Killen and Ip, 1999).

Understanding such processes is critical for correctly interpreting in situ and ground-based measurements, and making predictions for as-yet unexplored objects. Interest in the Moon's exosphere has increased recently with the upcoming 2013 launch of the Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft, which carries a neutral mass spectrometer capable of observing species in the mass range 1–150 amu (Mahaffy et al., 2009). Following lunar measurements of He, Ar and (spacecraft-delivered) H_2O during the Apollo era, a landmark measurement by Potter and Morgan (1988) observed Na and K using Earth-based limb measurements. Smith et al. (1999) later discovered that the lunar Na exosphere merges into a tail plume of escaping atoms that stretches hundreds of thousands of km from the Moon. The apparent correlation of the luminosity of the Na tail with a Leonid shower (Wilson et al., 1999) suggests meteoroid impacts as a source, at least occasionally. The presence of Na and K in the lunar exosphere hints that other regolith constituents escape as atoms and molecules in impact-generated vapor clouds; simulations by Sarantos et al. (2012) predict that the LADEE observations will provide quantitative information on metals as well as O, Si and other regolith-derived species. At Mercury, ground-based observations (Killen et al., 2005) demonstrated the presence of exospheric Ca, thought to be generated by either ion sputtering or micrometeoroid impact. The Mercury Surface, Space Environment, Geochemistry, and Ranging (MESSENGER) mission carried an optical spectrometer which later observed Ca in situ, along with Mg (McClintock et al., 2009) consistent with micrometeoroid vaporization (Sarantos et al., 2011), along with other species.

In the laboratory, valuable experiments have been performed (Sugita et al., 1998, 2003) using spectroscopic techniques to analyze the vapor produced in macroscopic impacts ($d \sim 1$ mm, $v < 7$ km/s). A variety of power laws for intensity as a function of projectile speed were found for different emission lines and bands for the atomic and molecular species present, suggesting that the impact-vapor contribution to the exosphere is the result of a complex chain of chemical and physical processes. Additional clues to impact vapor composition come from the *LCROSS* lunar impact (Schultz et al., 2010), which demonstrated that OH and other volatile species may be liberated in significant quantities from impacts. However, little is known about the neutral gas component from *microscale* impacts. In contrast to sporadic larger impacts, uniform, continuous bombardment by micrometeoroids delivers most of the mass flux to the Moon (Grün et al., 1985). Microcrater volumes and their scaling with projectile mass and velocity in ice (Eichhorn and Grün, 1993) and other materials have been measured in the laboratory; similar efficiency estimates and scaling laws exist for charge as a function of projectile mass and speed (Göller and Grün, 1989, e.g.) as a consequence of the many

---

* Corresponding author.
E-mail address: andrew.collette@lasp.colorado.edu (A. Collette).

0019-1035/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.icarus.2013.09.009

missions (Srama et al., 2004, e.g.) relying on impact ionization as a space-borne dust detection mechanism. However, the partitioning of the excavated mass between solid ejecta, neutrals and charged particles has never been established, nor has the efficiency of neutral gas generation been tested as a function of projectile mass and velocity, to determine if the theoretical scaling arguments are appropriate.

We describe a series of experiments in which the quantity of gas released from the impact of micron- and submicron-sized iron dust grains is directly measured, as a function of projectile mass and velocity. Individual grains are electrostatically accelerated into a hot-filament ionization gauge maintained at ultra-high vacuum conditions, and the local pressure increase is recorded for each impact. The quantity of liberated neutrals observed is consistent with a power law in mass and velocity.

2. Experiment design

Fig. 1 shows the experimental arrangement, using the dust accelerator facility at the Colorado Center for Lunar Dust and Atmospheric Studies (Shu et al., 2012). Charged micron- and submicron-sized iron spheres are launched one at a time from a dust source and accelerated through a 2.0 MV potential difference. Two in-line pickup detectors determine the speed and mass of each dust grain in flight; if the measured speed falls within a user-specified range, an electrostatic gate is opened, admitting the particle to the target chamber. Passing through a differential pumping section which isolates the ultrahigh-vacuum (10^{-10} torr) target chamber from the high-vacuum (10^{-8} torr) beamline, the particle enters the detection apparatus. Since the particle's mass can be inferred from its speed v, charge q and the acceleration potential Φ by $m = 2q\Phi/v^2$, the speed and mass of each particle producing an impact signal are recorded.

Fig. 2 shows the detection apparatus, which consists of a miniature hot-filament ionization vacuum gauge within a narrow, grounded stainless steel tube. Incoming dust particles pass through the transparent cylindrical grid assembly and strike the stainless-steel rear gauge housing. Neutral atoms and molecules liberated during the impact expand outward and enter the grid volume. Thermionic electrons from a heated filament are accelerated into the grid volume by a 150 V potential difference, and collisionally ionize a fraction of the neutrals. The resulting ions are drawn to the central collector wire, held near ground by the amplifier electronics, resulting in a measurable current. The collector current is measured as a function of time by a transimpedance amplifier (TIA) with a gain of 258 MΩ and smoothing time constant of $\tau = 148$ μs. The signal is bandwidth limited from 300 Hz to 1 MHz by amplifier stages following the TIA.

There are two contributions to the ion signal: the gauge-ionized neutral gas cloud, and background effects including impact-generated ions and electrons. Ionization is a well-known consequence of dust grain impact at the speeds encountered in this experiment (Auer and Sitte, 1968). In order to determine what portion of the signal was due to the presence of neutrals as opposed to charged particles or electromagnetic pickup, a series of control experiments were conducted. While maintaining all bias potentials within the gauge, the filament was turned off and an equal number of impacts were recorded.

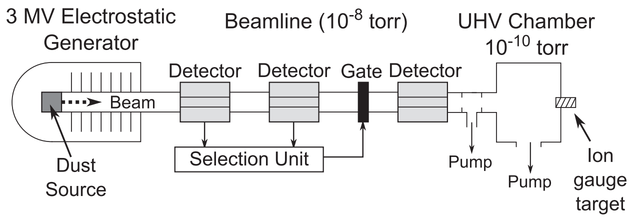

Fig. 1. Accelerator configuration. Individual dust grains traverse beamline detectors which measure their speed and charge; particles matching pre-set criteria are admitted to the experimental chamber. Differential pumping isolates the beamline from an ultrahigh-vacuum (10^{-10} torr) target chamber. Finally, the impact of a dust grain inside a miniature ion gauge housing (Fig. 2) creates a measurable pressure increase.

3. Results

Fig. 3a and b shows the TIA output for two particles of comparable mass and speed, for the cases of ionizer off and on respectively. The signal of (a) is due to background effects including collection of impact-generated charge, while (b) includes the contribution from the neutral gas cloud entering the ionizer volume.

The signals were integrated over time to determine the total charge collected. Fig. 4a shows the time-integrated charge collected as a function of the projectile mass (left axis), while Fig. 4b shows the mass-speed distribution of the dataset. The inverse dependence between mass and speed is a characteristic of all electrostatic accelerators; since the charge q on a spherical grain of radius r is proportional to the surface area (r^2), while the mass m is proportional to r^3, the speed $v = \sqrt{2q\Phi/m}$ scales as $1/\sqrt{r}$, where Φ is the acceleration potential difference.

The total charge Q collected for one impact is a function of (1) the amount of neutral gas released, the desired quantity; (2) the fraction-weighted average electron-impact ionization cross section across the neutral species present, at the fixed 150 eV electron energy used by the gauge; (3) the volume of the ionizer region; and (4) the duration over which the gas is present in the ionizer region. The analysis here does not address the distribution of the neutrals in velocity or angle, simply that gas appears in the ionizer region, is present for a certain length of time, and is then lost.

We can address (2) by examining the cross-sections for various species likely to be present, at the 150 eV electron energy used in the present experiment. Published cross sections for H_2O, N_2, Fe (the projectile material and main constituent of the target), as well as alkali metals commonly liberated (Postberg et al., 2009) by dust impacts range from 2.2 $Å^2$ (H_2O) to 5.5 $Å^2$ (Na), compared to N_2 at 2.5 $Å^2$. The ion gauge is calibrated for N_2 with an sensitivity uncertainty of 20%. The analysis presented here assumes the average cross section of the cloud is equal to that of N_2; the effect of assuming too small a cross section is that the density of the cloud will be overestimated by an equal factor. The analysis also assumes that the composition of the cloud is not a strong function of the mass or speed of the projectile over the ranges tested.

The ionizer volume V (3) is known from the mechanical design of the gauge and is 760 mm^3. The duration (4) over which the gas is present in the ionizer region varies from impact to impact and is determined from the experimental data. The TIA time series with the ionizer on (one example of which is shown in Fig. 3b) are used to determine a characteristic timescale. Defining the characteristic time T as the period between the initial sharp rise and decay to 20% over baseline, $T = 390 \pm 167$ μs. No particular dependence between T and the projectile speed v or mass m was identified.

Since the ion gauge calibration factor C provides density per unit collector current, the quantity QC represents a time-integrated density. We can use this information to estimate the total quantity of neutral particles N which pass through the ionizer:

$$N = \frac{QC}{T}V.$$

It should be noted that this treatment only measures the fraction of gas which passes through the grid volume of the gauge. Gas which