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Secondary electron emission from lunar soil: Yields, energy distributions, and charging effects

Catherine A. Dukes, Raúl A. Baragiola*

Laboratory for Atomic and Surface Physics, University of Virginia, Charlottesville, VA 22904, United States of America

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ABSTRACT

We report the electron emission and charging of sub-mature lunar highland soil 61241 by electron impact under ultra-high vacuum for 40–2000 eV electrons. The energy distribution of emitted secondary electrons was measured as a function of primary electron energy under neutral charging conditions, and electron energy loss spectroscopy was used to determine the ~8 eV band gap. Total electron yields were obtained with low electron fluxes. Imaging the soil with a Scanning Auger Microprobe using 10 keV electrons revealed differential grain motion induced by charging in ultra-high vacuum.

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1. Introduction

1.1. Electrostatic charging at the moon

The electrostatic charging of objects in space results from a balance of currents, derived from electrons (mostly) and ions transferring between the surface and its radiation environment (Whipple, 1981). Lunar surface potential measurements, due to photoelectron emission and plasma currents, range from ~+10 V to -4 kV with respect to the surrounding plasma. On average, the lunar surface potential is positive over most of the sunlit hemisphere, due to dominance of photoelectric emission from solar radiation (Manka and Michel, 1974; Freeman and Ibrahim, 1975). On the night side, the potential is negative, with values ranging from -10 to -100 V to several kilovolts when the Moon enters the energetic plasma environment of the terrestrial magnetotail (Lindeman et al., 1973; Freeman and Ibrahim, 1975; Benson, 1977; Halekas et al., 2002). Recent measurements of near surface electrons with the Lunar Prospector electron reflectometer indicate night-side surface potentials up to -4.5 kV during energetic particle events or during magnetotail crossings (Halekas et al., 2011; Poppe et al., 2011).

It has been suggested that electrostatic charging on the Moon can result in the levitation of charged dust, which may be responsible for the lunar “horizon glow” and light streamers photographed by Surveyor cameras (Rennilson and Criswell, 1974), and

for the peculiar behavior of the Apollo 17 Lunar Ejecta and Meteorite surface package near the morning and evening terminators (O'Brien, 2011). Dust levitation is difficult to model with any accuracy because of the lack of experimental data on particle and photon-induced charging of lunar soil, including total electron yields and energy distributions of ejected electrons. Even the most elaborate models of dust levitation are not yet able to discuss in detail the microscopic process of electrostatic forces overcoming adhesion, the stochastic nature of the charging process, or the mechanism by which the previously levitated grains rejoin the regolith.

Charging of the lunar surface is governed by time-varying fluxes of electrons and ions from the solar wind (Abbas et al., 2010), of photoelectrons ejected by UV photons (Feuerbacher et al., 1972; Sternovsky et al., 2008), and micrometeorite impacts (Baragiola 1994; Ratcliff et al., 1996). Although a description of charging in terms of continuous currents is convenient and customary in analytical descriptions, the fact that the charge variations are discrete has important implications. For instance, macroscopic potentials that can be deduced from observations or experiments are not sufficient to describe the motion of freed charges. A surface that is, on average, electrically neutral, may have inhomogeneous microscopic charging with large local electric fields that strongly affect inter-particle adhesion. Modeling microscopic charging of airless bodies requires detailed calculations of photon and charged particle induced electron emission that depends on soil properties, incident fluxes, and on surface topography, which affect the flow of electrons and ions in the plasma (Farrell et al., 2008) differently depending on position, altitude, and surface roughness (macroscopic and microscopic).

* Corresponding author. Tel.: +1 434 982 2907.

E-mail address: raul@virginia.edu (R.A. Baragiola).

1.2. Secondary electron emission

We note that currently, there is no alternative to laboratory measurements. The complexity of secondary electron emission is such that no accurate theory exists that can be used in astronomical applications. Electron emission from electrical insulators, such as most lunar material, is a difficult topic because of the existence of time-dependent charges with unknown lifetimes and mobility. In addition, the specific type of insulator will define the minimum energy required to produce secondary electron emission, the ionization potential of the solid. This value is given by the sum of the band gap E_G and the electron affinity of the surface (Riccardi et al., 2004). Electrons may be excited directly from the valence band or core levels or by Auger processes, after a projectile collision or through the collision cascade in the solid that leads to multiplication of the excited electrons (Baragiola, 1993). Energetic electrons (primary or secondary) can excite electrons in the solid to energies larger than twice the band-gap, which can then produce further excitation in the materials. In addition, not only valence, but also inner-shell electrons, can be excited and subsequently decay via Auger electron emission. By convention, the total electron emission from surfaces, σ , is divided in two components, defined by an ejection energy $\varepsilon=50$ eV that separates the lower energy “true secondary electrons” from the higher energy backscattered or rediffused primary electrons. Thus, $\sigma=\delta+\eta$, where δ is the secondary electron yield and η is the yield of rediffused primaries. The conventional separation of σ into components is practical but unphysical, since electrons are indistinguishable quantum particles, and it is not possible to determine whether an ejected electron is secondary or a backscattered primary. This convention also fails for incident electron energies below 50 eV.

Important parameters in secondary electron emission are: (1) the total yield $\sigma(E_p)$, the number of secondary electrons emitted per incident primary electron of energy E_p , (2) the electron energy distributions $N(\varepsilon)$, and (3) the crossover energies E' and E'' , where $\sigma=1$, and there is perfect charge balance between the incoming and outgoing electron current. It is also at the crossover energies that the surface potential changes polarity. At incident energies $E_p < E'$ and $E_p > E''$, the yield (σ) is < 1 and the surface charges negatively; at energies $E' < E_p < E''$ the surface charges positively and σ is > 1 . Changes in surface potential due to charging alter the energy at which the primary electrons strike the surface. The significance of the cross over energies is that they represent a point of charge equilibrium under continuing irradiation. If the charges are not compensated by conduction, the surface potential becomes increasingly negative for $E_p > E''$ retarding incident electrons toward E'' . For $E_p < E'$, the surface potential grows negatively up to the electron acceleration voltage, retarding incident electrons toward zero kinetic energy. For energies between E' and E'' , where the surface charge is positive under electron bombardment, continued irradiation causes the primary impact energy to increase with increasing surface charge, shifting the impact energy toward E'' . This implies that, in the absence of leakage current and continued electron impact, the total electron yield equilibrates at unity for all primary energies.

Electrons incident on the lunar surface can be absorbed by the soil, transmitted (through thin grains), or be backscattered into vacuum. This latter process can account for up to tens of percent of the primary flux. The energy distribution of secondary electrons is determined by the cascade of electron–electron collisions inside the solid, and by the energy-dependent transmission of the surface barrier, the electron affinity (Riccardi et al., 2004). The energy distribution $N(\varepsilon)$ of the emitted electrons is important for positive surface charging because, in this case, electrons with energy higher than the surface potential are able to escape and can balance the incoming charge.

In this work we report initial results of laboratory studies aimed at quantifying and understanding secondary electron emission and charging of bulk lunar soil (not single grains) under electron impact. This investigation, conducted in ultra-high vacuum, measured secondary electron yields and energy distributions and observed charging and the motion of regolith particles in an imaging electron microprobe.

2. Experimental methods

We investigated electron emission from Apollo 16 sub-mature ($I_s/FeO=47.0$), lunar highland soil 61241, which has a particularly low glass content, 3.3%. Grain size fraction for this soil is less than 1 mm, with an average particle size of 117 μm (Graf, 1993). The soil was fixed with conductive, water-based, silver paste (Pelco High Performance Silver Paste) to a tantalum substrate since our instrumentation requires samples to mount vertically for data collection. Sprinkling, with no compaction, onto the silver paste allowed the possibility of multiple grain layers. Greater than 95% coverage was ascertained by optical microscope. In-situ low-energy oxygen plasma was used to clean carbon and atmospheric surface contaminants from the soil before analysis (Dukes and Baragiola, 2010). Auger electron microscopy (AES) ascertained that the sample surface was clean and that signal was derived from the soil and not the silver paste adhesive.

For measurement of the total secondary electron yield (σ), a special 304 stainless steel cup was designed to hold the lunar soil, very similar to the setup used successfully at Orsay, (e.g., Boubaya and Blaise, 2007) to study secondary electron emission from insulators. Optical imaging shows good coverage by the soil over the area seen by incident electrons (cup center). The sample cup was electrically isolated by an alumina spacer from a stainless steel collection cap with a small (1 mm) aperture to admit primary electrons. The sample and cup were baked within the vacuum chamber for 48 h at ~ 150 °C to remove adsorbed water from the analysis chamber walls, cup/cap, and sample surface. Soil 61241, mounted with Ag paste on an Al platen, was also used for electron charging experiments under 10 keV electrons.

Electron emission experiments were conducted in an ultra-high vacuum (base pressure: $\sim 10^{-10}$ Torr) Physical Electronics 560 XPS/SAM system, equipped with a low energy electron gun mounted concentric to the double-pass, cylindrical-mirror electron energy analyzer (CMA) for electron irradiation and AES analysis. An X-ray source is fixed perpendicular to the CMA for X-ray photoelectron (XPS) measurements. The spectrometer was used for measurement of secondary electron distributions, as well as for surface characterization prior to $N(\varepsilon)$ and band gap measurements. XPS is a quantitative surface analytical technique that uses mono-energetic X-rays that eject electrons with an energy determined by their binding energy with respect to the Fermi level, originating from a thin surface layer (2–4 nm thick, depending on the photoelectron energy). Quantitative information is obtained by incorporating the instrument sensitivity for each elemental transition.

To measure secondary electron energy distributions, primary electrons were incident along the effective surface normal, while backscattered and secondary electrons emitted with an angle of $42.3^\circ \pm 3.5^\circ$ in a cone around the incident beam were energy analyzed by a double-pass CMA. Due to the granular structure of the soil, the actual incidence angle of the electrons varied widely; as a result secondary electron emission from rough samples is insensitive to the average angle of incidence (Bruining, 1954). The spectrometer was operated at constant pass energy of 40 eV, with a resolution of 0.2 eV independent of electron energy. A -5 V bias with respect to the grounded entrance grid of the CMA was

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