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Photoelectric dust levitation around airless bodies revised using realistic photoelectron velocity distributions

H. Senshu [a,*], H. Kimura [b], T. Yamamoto [c], K. Wada [a], M. Kobayashi [a], N. Namiki [d,e], T. Matsui [a]

[a] Planetary Exploration Research Center, Chiba Institute of Technology, 2-17-1, Tsudanuma, Narashino, Chiba 275-0016, Japan
[b] Graduate School of Science, Kobe University, c/o CPS (Center for Planetary Science), Chuo-ku Minatojima Minamimachi 7-1-48, Kobe 650-0047, Japan
[c] Center for Planetary Science (CPS) c/o Integrated Research Center of Kobe University, 7-1-48, Minamimachi, Minatojima, Chuo-ku Kobe 650-0047, Japan
[d] RISE Project Office, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
[e] Department of Astronomical Science, The Graduate University for Advanced Studies (SOKENDAI), Japan

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ABSTRACT

The velocity distribution function of photoelectrons from a surface exposed to solar UV radiation is fundamental to the electrostatic status of the surface. There is one and only one laboratory measurement of photoelectron emission from astronomically relevant material, but the energy distribution function was measured only in the emission angle from the normal to the surface of 0 to about $\pi/4$. Therefore, the measured distribution is not directly usable to estimate the vertical structure of a photoelectric sheath above the surface.

In this study, we develop a new analytical method to calculate an angle-resolved velocity distribution function of photoelectrons from the laboratory measurement data. We find that the photoelectric current and yield for lunar surface fines measured in a laboratory have been underestimated by a factor of two. We apply our new energy distribution function of photoelectrons to model the formation of photoelectric sheath above the surface of asteroid 433 Eros. Our model shows that a 0.1 μm-radius dust grain can librate above the surface of asteroid 433 Eros regardless of its launching velocity. In addition, a 0.5 μm grain can hover over the surface if the grain was launched at a velocity slower than 0.4 m/s, which is a more stringent condition for levitation than previous studies. However, a lack of high-energy data on the photoelectron energy distribution above 6 eV prevents us from firmly placing a constraint on the levitation condition.

1. Introduction

When an airless object is irradiated with solar ultraviolet (UV) photons, electrons are emitted from the surface of the object due to photoelectron emission. The emitted electrons charge up the surface positively and make a thin photoelectric sheath above the surface. As a result, photoelectrons generate an upward electrostatic field in the photoelectric sheath.

The structure of photoelectric sheath was theoretically studied since late 1960s to meet requirements for aerospace engineering (e.g., Guernsey and Fu, 1970; Grard and Tunaley, 1971; Grard, 1973). The structure is determined by the total flux and velocity distribution function of photoelectrons emitted from a surface. The formulation of the sheath structure obtained in the previous studies can be applied to an airless object exposed to solar UV radiation.

The surface of an airless object suffers from not only solar UV irradiation but also bombardments of micrometeoroids. The latter produces small fragments or dust grains on the surface of the object. Since dust grains irradiated with solar UV photons also charge up positively due to photoelectron emission, they are subjected to an electric repulsion force from the positively charged surface. If the repulsion force overcomes the gravitational force of the airless object, the dust grains are accelerated upwards (Havnes et al., 1987; Lee, 1996; Stubbs et al., 2006).

To trace the motion of dust grains within a photoelectric sheath is tricky because the repulsion force depends on both the electrostatic field and the electric charges of the grains that change with time (Nitter et al., 1998; Colwell et al., 2005; Poppe and Horányi, 2010; Hirata and Miyamamoto, 2012). In addition, we need a model of photoelectric sheath. Nitter et al. (1998) applied a

* Corresponding author.
E-mail address: hsenshu@gmail.com (H. Senshu).

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photoelectric sheath model given by Guernsey and Fu (1970) to explain the formation mechanism of spokes in Saturnian rings. Colwell et al. (2005) simulated the motion of 0.5 μm-radius dust grains on the asteroid Eros by using a photoelectric sheath model given by Grard and Tunaley (1971). They found that the 0.5 μm-radius dust grains can levitate above the surface of Eros for a long time to make a 'pond' structure (cf. Veverka et al., 2001). Hirata and Miyamamoto (2012) applied the same model to Saturnian icy satellite Atlas and found that the origin of its unusual smooth surface can be explained by a lateral movement of dust grains within the photoelectric sheath of the satellite.

Grard and Tunaley (1971) demonstrated that a photoelectric sheath strongly depends on the velocity distribution function of photoelectrons associated with the perpendicular motion of the electrons. Previous numerical studies on the dynamics of electrically charged dust particles in a photoelectric sheath commonly assumed a Maxwellian distribution (Colwell et al., 2005; Poppe et al., 2012; Hirata and Miyamamoto, 2012). On the contrary, laboratory measurements of photoelectron emission from lunar surface fines showed that the energy distribution of photoelectrons is not Maxwellian (Feuerbacher et al., 1972; Willis et al., 1973). Poppe and Horányi (2010) attempted to incorporate the non-Maxwellian energy distribution of photoelectrons emitted from lunar fines into their particle-in-cell (PIC) simulations, by implicitly assuming a unidirectional motion of photoelectrons. However, their assumption contradicts the nearly isotropic angular distribution of photoelectron flux from the lunar surface measured in situ by the Apollo 14 charged-particle lunar environment experiment (CPLEE) (Reasoner and Burke, 1972, 1973).

In this study, we develop a numerical model on the structure of photoelectric sheath and apply the model to trace dust motion above the surface of asteroid 433 Eros. Our model provides a new formulation for the distribution function of vertical velocity based on an experimental measurement by Feuerbacher et al. (1972) and photoelectron sticking onto a levitating dust grain. In the next section, our numerical model is briefly explained. Section 3 gives our numerical results and in Section 4, we will discuss the results and end with our conclusions.

2. Basic equations

2.1. Vertical velocity distribution function of photoelectrons

The velocity distribution function of photoelectrons emitted from a surface is a key to understand the structure of the photoelectric sheath. Although the function could be determined experimentally, laboratory measurements are usually carried out for the materials used in industry or aerospace engineering such as metals and silicone. There is one and only one measurement for the properties of astronomically relevant material (Feuerbacher et al., 1972, see also Willis et al., 1973). Feuerbacher et al. (1972) measured the photoelectric properties of lunar soil samples as a function of photon energy and calculated the velocity distribution function of photoelectrons under solar UV irradiation. It is to be noticed that they derived the energy distribution function of photoelectrons, $\tilde{p}(\psi)$, for radial energy in the emission angle of 0 to about $\pi/4$ (see Fig. 1 of Feuerbacher et al., 1972). In contrast, one needs a distribution function of vertical velocity in the emission angle of 0 to $\pi/2$ to calculate the structure of photoelectric sheath. The distribution function of horizontal velocity is also required to calculate the sticking rate of sheath electrons onto a levitating dust grain.

We have scanned and digitized the energy distribution function of photoelectrons from lunar samples shown by Fig. 6 in Feuerbacher et al. (1972) to approximate the vertical velocity distribution function by an analytic expression. In the digitized data, we are unable to determine the high-energy (>6 eV) component of photoelectrons, while Feuerbacher et al. (1972) mentioned that the fraction of high-energy photoelectron is extremely low. We will discuss the effect of high-energy component of photoelectrons on the vertical structure of photoelectric sheath later.

The angle-dependent energy distribution function $\Delta\zeta$ of photoelectrons is expressed as (see Appendix A for the derivation)

$$\Delta\zeta = \frac{1}{2\pi}\left(\frac{m}{e}\right)\sqrt{\frac{m}{2ew_{\rm f}}}A^{-1}\sqrt{\frac{\phi/w_{\rm f}}{1+\phi/w_{\rm f}}}\frac{\tilde{p}(\psi)}{\sqrt{1+\frac{\psi}{w_{\rm f}}}-\sqrt{1+\frac{\psi}{2w_{\rm f}}}} \quad (1)$$

where m and $-e<0$ are the mass and charge of a single electron, respectively and $w_{\rm f}$ is the work function. The total and vertical kinetic energies of a photoelectron, ψ and ϕ, are calculated from the vertical and horizontal velocities of the photoelectrons, v and $v_{\rm r}$, by

$$e\psi = \frac{1}{2}m(v^2+v_{\rm r}^2), \quad (2)$$

$$e\phi = \frac{1}{2}mv^2. \quad (3)$$

The coefficient A in Eq. (1) is given by (see Appendix A)

$$A = \int_0^\infty \tilde{p}(\psi)\frac{\sqrt{1+\frac{\psi}{w_{\rm f}}}-1}{\sqrt{1+\frac{\psi}{w_{\rm f}}}-\sqrt{1+\frac{\psi}{2w_{\rm f}}}}d\psi. \quad (4)$$

By using Eq. (1), the distribution function, $F(v)$, of the vertical velocity is given by

$$F(v) = 2\pi\int_0^\infty \Delta\zeta v_{\rm r}\,dv_{\rm r},$$
$$= \sqrt{\frac{m}{2ew_{\rm f}}}A^{-1}\sqrt{\frac{\frac{mv^2}{2ew_{\rm f}}}{1+\frac{mv^2}{2ew_{\rm f}}}}\int_{mv^2/2e}^\infty \frac{\tilde{p}(\psi)}{\sqrt{1+\frac{\psi}{w_{\rm f}}}-\sqrt{1+\frac{\psi}{2w_{\rm f}}}}d\psi. \quad (5)$$

Feuerbacher et al. (1972) determined the work function for lunar surface fines to be $w_{\rm f}=4.97$ eV based on the Fowler method.

2.2. Vertical structure of photoelectric sheath

The number density of photoelectrons near the surface, N_0, is determined by (cf. Grard, 1973)

$$I_{\rm s} = \frac{N_0}{2}\int_0^\infty vF(v)\,dv, \quad (6)$$

where $I_{\rm s}$ is the total photoelectron flux from irradiated surface and related to the photoelectron flux determined by an experimental study, $\tilde{I}_{\rm s}$, by

$$I_{\rm s} = A\tilde{I}_{\rm s}. \quad (7)$$

Inserting Eqs. (7) and (5) into Eq. (6), we get

$$N_0 = 4\sqrt{\frac{m}{2ew_{\rm f}}}\tilde{I}_{\rm s}A^2$$
$$\times\left[\int_0^\infty \frac{1}{w_{\rm f}}\sqrt{\frac{\phi/w_{\rm f}}{1+\phi/w_{\rm f}}}\left\{\int_\phi^\infty \frac{\tilde{p}(\psi)}{\sqrt{1+\frac{\psi}{w_{\rm f}}}-\sqrt{1+\frac{\psi}{2w_{\rm f}}}}d\psi\right\}d\phi\right]^{-1}, \quad (8)$$