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12. Photoelectric Charging of Partially Sunlit Dielectric Surfaces in Space

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1. INTRODUCTION

Spacecraft surfaces – or portions thereof – are often made of highly resistive dielectric material. During part of its orbit, a spacecraft assumes configurations where a section of the surface is sunlit and the rest is in darkness. Moreover, as the orbit progresses, this sunlight-shadow configuration changes, causing the sunlit area to expand or contract. These effects can give rise to special photoelectric charging circumstances.

In this paper, we outline some of these circumstances. Some applications of these circumstances to the problem of photoelectric charging of localized sunlit patches in the dark sunset terminator region of the Moon has been discussed elsewhere.[1,2] In the following, we discuss charging due to the photoelectric effect alone. The presence of an ambient plasma modifies the situation, but the considerations discussed here still apply. However, the discussion of this paper is

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limited to cases where the spin period of the spacecrafts is of the order of or longer than the relevant time-scales that we define in Section 3.

2. CHARGE SEPARATION BETWEEN SUNLIT AND DARK AREAS

Figure 1 is a sketch of a partially sunlit dielectric surface. Photoelectrons emitted from the sunlit area can have three types of trajectories: Type A trajectory takes the electrons beyond a predefined limiting distance (such as a Debye-length) such that these electrons do not return to the sunlit area; Type B trajectory takes the electrons to the dark area to locations where the electrons are retained due to the high resistivity of the dielectric material. Type A and Type B electrons are lost to the sunlit area. Finally, Type C trajectory brings the electrons back to the sunlit area without changing the net charge of the area. A steady state is attained when all emitted electrons assume Type C trajectories.

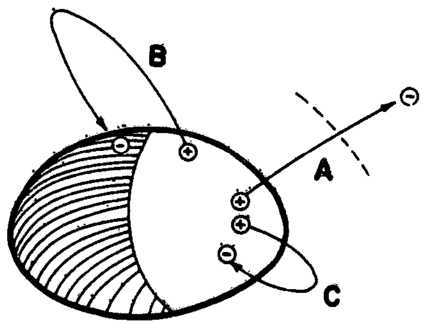

Figure 1. The Three Possible Types of Photoelectron Trajectories: Type A terminates beyond a predefined limiting distance, Type B on the dark area, and Type C on the sunlit area

A little consideration will show – as numerical computations do indeed show[1] – that the accreted electrons on the dark area tend to concentrate near the edge of the sunlight-shadow boundary (with the exception of the case where a dark area is not contiguous with the sunlit area). As we shall explain presently, the positive charges on the sunlit area also tend to concentrate near the sunlight-shadow boundary. This boundary thus represents a region of intense multipole electric fields.

3. CONDUCTOR-LIKE BEHAVIOR OF THE SUNLIT AREA

Since the photoemitting area is dielectric, one would commonly assume that the positive charges on the area are immobile. However, this assumption is likely to lead to erroneous results. The positive charges on a photoemitting dielectric surface possess an <u>effective</u> mobility – which causes them to tend to achieve a surface density distribution appropriate to a conducting surface. This is an effect which does not readily emerge from the conventional treatment of the charging problem by solving the Poisson-Vlasov equations. This effect thus represents a shortcoming of the Poisson-Vlasov treatment.

We present below a semiquantitative and heuristic argument to demonstrate the conductor-like behavior of a photoemitting dielectric surface. A full analysis of the problem cannot be undertaken without reference to a specific surface geometry with a specified photon and particle environment.

Consider for simplicity a flat sunlit dielectric surface of finite extent in space. For the moment we ignore the presence of any ambient plasma. Let $N(\epsilon)\,d\epsilon$ represent the flux of the emitted electrons in the energy range ϵ to $\epsilon + d\epsilon$, and let ϵ_0 be the highest effective energy of the emitted electrons. In the steady state, all emitted electrons return to the surface (that is, they execute Type C trajectories) and there is a steady charge density of n positive charges per unit area at any point on the surface. Under the assumption of charge immobility, this charge density has the same value over the entire surface.

The uniformity of the charge density over the entire surface gives rise to an electric field component $E_{\parallel}$ parallel to the surface at any point on the surface. This field influences the Type C trajectories in such a way that the positive charges on the surface <u>appear</u> to be shifting in the direction of $E_{\parallel}$ so as to annul this field. The positive surface charges thus have an effective mobility which tends to prevent the development of a parallel electric field component. The result is that the surface charge distribution tends to resemble that on a conducting surface and hence the dielectric surface tends to be equipotential. The present effect, however, is better not described in terms of a conductivity, since the surface charges are constrained to move in two-dimensions.

We need, however, to examine the rate at which the redistribution of surface charges takes place in order to determine if this effect is indeed important. The criterion for the effect to be important is that the time-scale for surface charge redistribution be smaller than or of the order of the time-scale over which the surface charge density n is established. The latter time-scale has a <u>lower limit</u>

$$\tau_n = n / \int_0^{\epsilon_b} N(\epsilon)\, d\epsilon \qquad (1)$$

but is almost certainly larger than this value.

To illustrate the effective mobility, we make the following simplifying assumption: We assume that a typical value $E_{\parallel}$ characterizing the entire surface has a constant value to a height h above the surface and vanishes above this height. An electron of energy ϵ typically spends a time $t \sim h \sqrt{m/\epsilon}$ in this field. During this time, the electron has its trajectory altered (from that in absence of a parallel electric field component) so that it is displaced through a distance $\Delta r \sim h^2 e E_{\parallel}/\epsilon$ in the direction antiparallel to $E_{\parallel}$ as shown in Figure 2 (e = electronic charge). This displacement is equivalent to that of a positive surface charge through a distance Δr in the opposite direction.

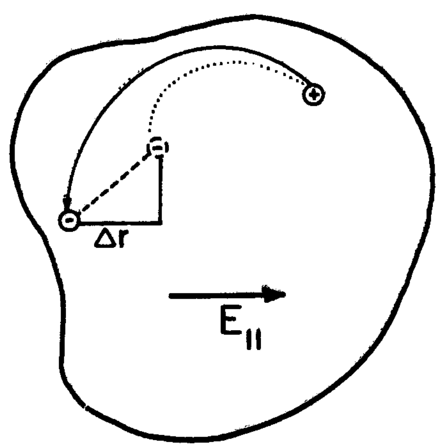

Figure 2. The Dotted Line Represents Trajectory of a Photoelectron Returning to the Sunlit Area in Absence of an Electric Field Component Parallel to the Surface at the Surface. When such a field component $E_{\parallel}$ is present, the trajectory is altered and is represented by the solid line. The result is a displacement of the electron through a distance Δr antiparallel to $E_{\parallel}$. This is equivalent to a displacement of a positive surface charge through a distance Δr parallel to $E_{\parallel}$ - tending to counteract $E_{\parallel}$

The value of Δr averaged over all electron energies may be found from

$$\langle \Delta r \rangle = h^2 e E_{\parallel} \frac{\int_0^{\epsilon_0} N(\epsilon)\, \epsilon^{-1}\, d\epsilon}{\int_0^{\epsilon_0} N(\epsilon)\, d\epsilon} . \qquad (2)$$

However, regardless of how $\langle \Delta r \rangle$ is calculated, the rate at which the surface charges move across a unit length perpendicular to $E_{\parallel}$ is approximately

$$\dot{N}_{\parallel} = \langle \Delta r \rangle \int_0^{\epsilon_0} N(\epsilon)\, d\epsilon \qquad (3)$$

An upper limit to the charge distribution time-scale is now given by

$$\tau_{re} \approx n \langle \Delta r \rangle / \dot{N}_{\parallel} = \tau_n . \qquad (4)$$

Our approximate analysis thus shows that τ_{re} and τ_n (the lower limit) are of the same order, showing that the effect that we suggest is significant.

Once the surface has achieved a steady state with a conductor-like charge distribution, the surface charges remain in a steady state of flux and the photoelectrons return to such locations on the surface that the charge distribution remains unchanged subsequently.

If the sunlit portion of the surface is partly dielectric and partly conducting, then the above effect suggests that the conductor-dielectric boundary would not represent as sharp a conductivity discontinuity as one would normally assume. The Type C trajectories would cause the surface charges to migrate across the conductor-dielectric boundary at a nontrivial rate.

The conductor-like charge distribution on the sunlit area implies a concentration of positive charges near the sunlight-shadow boundary — as mentioned earlier.

4. CHANGE IN POTENTIAL OF THE SUNLIT AREA AT EXPANSION OR CONTRACTION

When the sunlit area expands or contracts, the steady state established with a given sunlight-shadow geometry no longer holds. With the changing sunlight-shadow configuration, the surface tends to continually achieve new steady states. Whether or not such steady states are actually attained at each step depends on the rate at which the expansion or the contraction takes place.

Let ϕ, Q, A and C be the instantaneous potential, net charge, total sunlit area and the capacitance of this area respectively. Let $\sigma(\underline{r})$ be the surface charge density, which is a function of the position $\underline{r}$ on the surface. Then the development of the potential with changing area may be expressed analytically as

$$\frac{d\phi}{dA} = -\frac{Q}{C^2}\frac{dC}{dA} + \frac{1}{C}\frac{d}{dA}\left[\Sigma_i \sigma_i \Delta A_i\right] \tag{5}$$

where ΔA_i represents an elemental surface area and where the summation extends over the entire sunlit area. The first term on the righthand side of this equation simply gives the change in potential due to the change in capacitance of the sunlit area. The second term gives the change in potential due to the change in the net charge of the sunlit area arising from two causes: (1) the loss or gain of area, and (2) the change in net charge by losing photoelectrons to newly shadowed positively charged portions of the surface, or by new photoemission from freshly annexed negatively charged dark portions of the surface. Using Eq. (5), the development of potential of a contracting or expanding sunlit area may be traced by using numerical simulation methods. We have presented elsewhere an example of such a method.[2]

Whether the potential of a contracting or expanding area increases or decreases with time depends on how the various terms in Eq. (5) compete. The major deciding factor is the rate of contraction or expansion – for this is what determines the attainment of steady states at the successive steps of contraction or expansion. In some cases, it is possible that the potential will increase with time, causing a "supercharging" of the sunlit area.

5. GENERAL CONCLUSIONS

The following general conclusions may be drawn from our discussion:

(1) Sunlight-shadow effects may substantially alter the charging situation for a dielectric surface. The sunlight-shadow boundary tends to be the site of intense multipole electric fields.

(2) Charges on a sunlit dielectric surface have a finite effective mobility. The charge distribution tends to resemble that on a conducting surface.

(3) A boundary between a conducting and a dielectric surface may not represent a conductivity discontinuity when this boundary is sunlit. Charges may migrate at a nontrivial rate across the boundary.

(4) A contracting or expanding sunlit area may experience a "supercharging."

The presence of an ambient plasma will modify these conclusions to an extent depending on the parameters of the plasma medium and the strength of the radiation field.

Acknowledgments

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