LUNAR DUST AND DUSTY PLASMA PHYSICS. T. L. Wilson, NASA, Johnson Space Center, Houston, Texas 77058 USA.

Introduction: In the plasma and radiation environment of space, small dust grains from the Moon's surface can become charged. This has the consequence that their motion is determined by electromagnetic as well as gravitational forces. The result is a plasma-like condition known as "dusty plasmas" with the consequence that lunar dust can migrate and be transported by magnetic, electric, and gravitational fields into places where heavier, neutral debris cannot. Dust on the Moon can exhibit unusual behavior, being accelerated into orbit by electrostatic surface potentials as blow-off dust, or being swept away by moving magnetic fields like the solar wind as pick-up dust. Hence, lunar dust must necessarily be treated as a dusty plasma subject to the physics of magnetohydrodynamics (MHD). A review of this subject has been given before [1], but a synopsis will be presented here to make it more readily available for lunar scientists.

Dust Dynamics: Whenever dust becomes charged, interplanetary electromagnetic forces will alter the dynamics of such charged grains of matter in unexpected ways. Instead of following gravitational trajectories subject to Kepler's laws modified by Poynting-Robertson drag [2,3], charged dust can spiral about magnetic field lines similar to electrons and protons. It then behaves like the charged ion constituents (pick-up ions) of a planetary atmosphere or exosphere interacting directly with the solar wind [4-7] as in Figure 1.
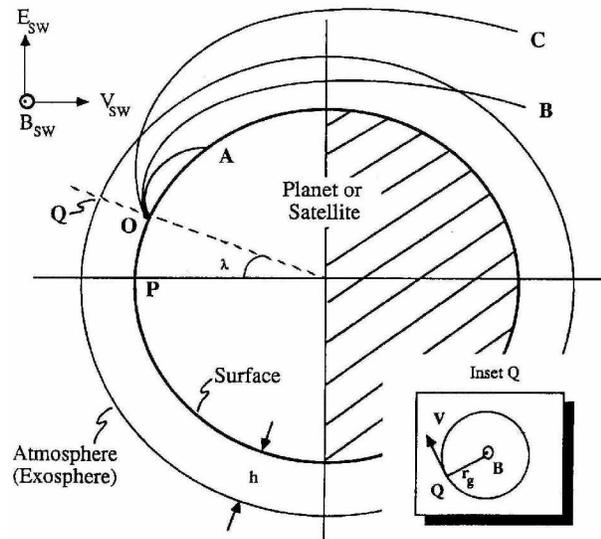
Figure 1. Illustration of the orbits of dust ejecta from and about the lunar surface [1].

The motion of a charged particle with a velocity v in an electric field E, a magnetic field B, and no gravitational field is subject to the Lorentz force F [8]

$$F = q(E + VxB) \qquad (1)$$

where q is the total charge, $V = v/c$, the particle has mass m, and c is the speed of light.

This classical picture of the relativistic electrodynamics of q changed, however, with the advent of space plasma physics where large-scale magnetic fields are in fact being formed and altered by MHD effects. An interplanetary space environment modifies the simple closed-system concept of Lorentz in (1) into an open system subject to external forces and currents of moving plasma and moving magnetic field lines B [1]. An important example in the solar system is the solar wind and the Sun's interplanetary magnetic field.

As plasma flows from the Sun a condition referred to as "frozen in flux" [9-11] occurs whereby the magnetic field lines are tied to the plasma and move with it, creating the interplanetary magnetic field. At the same time, an apparent electric field arises due to the VxB term in (1) which is sometimes described as an interplanetary electric field. This happens because in the theory of relativity, one can always find a frame of reference in which both electric and magnetic fields are present. That is understood by performing a simple Lorentz transformation (to first order in $V = v/c$) from a planetary rest frame (e.g., the satellite in Figure 1) to the coordinate system flowing with the plasma gas. The result modifies the electric field E as

$$E = E' - VxB . \qquad (2)$$

Alternatively, a space plasma is believed to be a condition of high, even infinite tensor conductivity σ, and the current from Ohm's law $J = \sigma E' = \sigma(E + VxB)$ must remain finite. σ can approach infinity only if $(E + VxB)$ goes to zero. The consequence is an interplanetary electric field

$$E_{SW} = - V_{SW} x B_{SW} \qquad (3)$$

seen in the surface rest frame **O** illustrated in Figure 1, where V_{SW} is the solar wind velocity vector.

A helpful visualization of the trajectories A, B, and C in Figure 1 is to neglect the gravitational forces (as did Lorentz) and imagine only E_{SW} and B_{SW}. Charged dust of charge-to-mass ratio q/m will orbit the magnetic field line B as depicted in the inset with a circular cyclotron frequency $\omega = qB/mc = V_{SW}/r_g$ and have a cycloidal trajectory with radius of gyration r_g.

The presence of E_{SW} in Equation (3) causes the cycloidal orbit to drift slowly in the direction of $E_{SW}xB_{SW}$

with a velocity $V_{Drift} = E_{SW}xB_{SW}/B^2$. It is as simple as drawing circles of radius r_g which osculate with V at Q (Figure 1 inset), and then allowing them to drift downwind in the direction of $E_{SW}xB_{SW}$. Examples are illustrated as the sequence A,B,C for bound, grazing, and unbound trajectories.

Again, the visualization for Equation (1) is the extreme case where the planetary gravitational field is turned off – the opposite of the conventional assumption where the magnetic and electric fields are turned off. The true physics of the matter is that both effects are present. The equation of motion in inertial coordinates fixed at the planet's center is actually

$$\ddot{r} = -\frac{GMr}{r^3} + \frac{q}{m}(E + \frac{\dot{r}}{c}xB) \qquad (4)$$

which results from a total "$F=ma$" force which is the sum of the gravitational Newtonian force (first term), and the Lorentz force (second term) from Equation (1). In Equation (4), G is Newton's gravitation constant ($G = 6.674x10^{-8}$ cm^3 g^{-1} s^{-2}), M is the planet's mass, r is the charged dust grain's position vector, and $\ddot{r}$ its acceleration vector ($\ddot{r} = a$ in "$F=ma$"). The first integral of motion for (4) is the inertial velocity $\dot{r} = v$. When $\dot{r}$ reaches an escape velocity due to the Lorentz force, or when its position r exposes it to certain orientations of the electric field E_{SW} in Figure 1, the charged dust grain is swept out of and away from the gravitational potential well by the interplanetary electric field which is basically performing work (as an external energy source) to get it off of the planet's surface.

Electrodynamic Surface Potentials: Equation (4) is not the end of the story because motion of the Moon in space will induce electrostatic surface charging due to precipitation and sputtering of energetic MHD plasma as it orbits through the Earth's plasma sphere and magnetosphere, as well as the solar wind, and photoelectrons produced by ultra-violet sunlight. The result is motionally induced surface electric fields E_o.

One can implement the effect of these into (4) by assuming two uniform hemispherical charge distributions created by differential plasma precipitation, producing an electrostatic levitation potential $\Phi_i = k_oQ/r$ for each side of the Moon ($i = 1,2$) with respect to the subsolar point [1], where Q is the total hemispherical surface charge and k_o is the Coulomb electrostatic constant. The electrostatic potential Φ has actually been measured for the Moon [12-14] to be as high as $|\Phi| \sim$ 200 V as it crosses the Earth's magnetospheric tail.

At the planetary surface one has $\Phi_o = k_oQ/r_o$, whereby $\Phi_o(\hat{r}) = \Phi_o/\hat{r}$ and $\hat{r} = r/r_o$ is in units of the planetary radius r_o. This is just an idealized case, noting again that the actual field $\Phi(\hat{r})$ is a Legendre polynomial and must be measured to solve the problem. However, Φ mimics scalar Newtonian Legendre-

polynomial gravitation identically. To first order, the planetary surface's electric field E_o is $|E_o(r)| = |$ -grad $\Phi_o|$ which gives $E_o(r) = \Phi_o r/r^3$. Substitution into (4) with $E = E_o + E^*$ yields the general equation

$$\ddot{r} = -\frac{kr}{r^3} + \frac{Z}{m}(E^* + \frac{\dot{r}}{c}xB) \qquad , \qquad (5a)$$

$$k = (GM - \frac{Z}{m}\Phi_o) \qquad (5b)$$

where $Z = Z_{Dust}q$ represents the effective total charge of the dust grain. E^* is any other ambient electric field such as E_{SW}. Whenever $\Phi_o = GMm/Z$, gravitation is cancelled out - and hence the term levitation.

Finally, dust grains have tensor rather than scalar material properties. Unlike a simple electron or proton, they have permittivities ε_{dust} and magnetic susceptibilities χ_{dust} that can increase 9-fold in complexity. Their conductivity σ is likewise a tensor. Hence, scalars have become tensors in the dust-grain dynamics of (5).

Conclusion: The motionally induced electric fields introduced by Lorentz as necessary consequences of the relativity of charge in motion play a pertinent role in the magnetohydrodynamics of charged dust on the Moon. The notion of electrostatic pick-up dust, akin to pick-up ion transport in interplanetary plasmas, proves very useful in the characterization of this process for the motion of lunar dust about its surface and into space. The general equation of motion involved is (5a,b) and not (4). Much of the unexpected behavior of charged dust grains can now be understood because (5a,b) cannot be solved without an *in situ* measurement of the scalar electrostatic levitation potential Φ. The commonplace assumption of (4) will always give an incorrect result when the surface potential $\Phi(\hat{r}) \neq 0$ and conductivity σ_{dust} has become a tensor.

References: [1] Wilson T.L. (1992), in *Analysis of Interplanetary Dust*, M. Zolensky *et al.* AIP Conf. Proc. **310**, 33-44 (AIP, NY). [2] Robertson H.P. (1937), *Mon. Not. Roy. Astron. Soc.* **97**, 423. [3] Burns J., *et al.* (1979), *Icarus* **40**, 1. [4] Grün E., *et al.* (1993), *Nature* **363**, 144. [5] Morfill G. and Grün E. (1979), *Planet. Space Sci..* **27**, 1269, 1283. [6] Manka R. and Michel F. (1971), *Proc. 2nd Lun. Sci. Conf.* **2**, 1717 (MIT Press, Cambridge). [7] Manka R. *et al.* (1973), *Lun. Sci.-III*, 504. [8] Lorentz H.A. (1915), *The Theory of Electrons*, 2nd edition, 14 and 198 (Dover 1952, NY). [9] Parker E.N. (1970), *Ap. J.* **160**, 383. [10] Cowling T. G. (1957), *Magnetohydrodynamics* (Interscience, NY). [11] Spitzer L. (1962) *Physics of Fully Ionized Gases* (John Wiley & Sons, NY). [12] Vondrak R. et al. (1974), *Geochim. et Cosmochim. Acta, Suppl. 4 (GCA)*, **3**, 1945. [13] Reasoner D. and Burke W. (1972), *J. Geophys. Res.* **77**, 6671. [14] Manka R. (1973), in *Photon & Particle Interactions with Surfaces in Space*, R. Grard ed., Reidel, 347-361.