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

Introduction: Small dust grains from the Moon’s surface can become charged in the plasma and radiation environment of space. One consequence of this is that their motion is determined by electromagnetic as well as gravitational forces. A plasma-like condition known as “dusty plasmas” results, with the additional consequence that lunar dust can migrate and be transported by magnetic, electric, and gravitational fields into places where heavier, neutral debris cannot. Hence, 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. Therefore, lunar dust must necessarily be treated as a dusty plasma subject to the physics of magnetohydrodynamics (MHD). Although this subject has been reviewed before [1], a short synopsis will be presented here to make it more readily available for investigators in NASA’s current Vision for Space Exploration which involves a proposed return to the Moon.

Dynamics of Dust: 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 [4-8].

The motion $\mathbf{v}$ of a charged particle in an electric field $\mathbf{E}$, a magnetic field $\mathbf{B}$, and no gravitational field is subject to the Lorentz force $F$ [9]

$$F = q(E + \frac{1}{c} v \times B) \quad (1)$$

where $q$ is the total charge and $c$ is the speed of light. Thinking of the velocity $v$ as the fraction $\mathbf{V} = v/c$ in (1) is equivalent to adopting units where $c = 1$.

The classical picture of the electrodynamics of $q$ charged, however, with the advent of space plasma physics since 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 $\mathbf{B}$ [1]. The solar wind and the Sun’s interplanetary magnetic field are important examples in the solar system.

A condition referred to as “frozen in flux” [10-12] occurs as plasma flows from the Sun 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 $\mathbf{V} \times \mathbf{B}$ term in Equation (1) which is sometimes described as an interplanetary electric field [4-8]. 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 $\mathbf{V} = v/c$) from a planetary rest frame to the coordinate system flowing with the plasma gas. The result modifies the electric field $\mathbf{E}$ as

$$\mathbf{E} = \mathbf{E}' - \mathbf{V} \times \mathbf{B} \quad (2)$$

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

$$E_{\text{SW}} = - V_{\text{SW}} \times B_{\text{SW}} \quad (3)$$

seen in certain rest frames, where $V_{\text{SW}}$ is the solar wind velocity vector.

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

The existence of $E_{\text{SW}}$ in Equation (3) causes the circular orbit or cycloid to drift slowly in the direction of $E_{\text{SW}} \times B_{\text{SW}}$ with a velocity $V_{\text{drift}} = E_{\text{SW}} \times B_{\text{SW}} / B^2$. It is as simple as drawing circles of radius $r_g$ which osculate with $V$, and then allowing them to drift downwind in the direction of $E_{\text{SW}} \times B_{\text{SW}}$. These include bound, grazing, and unbound trajectories – noting that $r_g$ is quite large for dust. All the charged dust grain has to do is get picked up by the solar wind and it is gone or swept away.

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

$$\ddot{r} = - \frac{GM \rho}{r^3} + \frac{q}{m}(E + \frac{\dot{r}}{c} \times B) \quad (4)$$
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 (\( G = 6.672 \times 10^{-8} \) cm\(^3\) g\(^{-1}\) s\(^{-2}\)), \( M \) is the planet’s mass, \( r \) is the charged dust grain’s position vector, and \( \mathbf{r} \) its acceleration vector (\( \mathbf{a} = \mathbf{F}/m \)). The first integral of motion for Equation (4) is the inertial velocity \( \dot{r} = v \). When \( \dot{r} \) reaches an escape velocity due to the Lorentz force terms, or when its position \( r \) exposes it to certain orientations of the electric field \( E_{SW} \), 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.

**Electrostatic Surface Potentials:** Equation (4) is only part 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 [1]. The consequence is motionally induced surface electric fields \( E_o \).

One can implement the effect of \( E_o \) into Equation (4) by assuming two uniform hemispherical charge distributions created by differential plasma precipitation, resulting in an electrostatic levitation potential \( \Phi_l = k_o Q / r_o \) 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 \( \Phi \) has actually been measured for the Moon [13-17] to be as high as \( \mid \Phi \mid \sim 200 \) V as it crosses the Earth’s magnetospheric tail.

At the Moon’s surface one has \( \Phi_o = k_o Q / r_o \), whereby \( \Phi (\hat{r}) = \Phi_o \hat{r} / r \) 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, \( \hat{r} \) mimics scalar Newtonian Legendre-polynomial gravitation identically. To first order on the planetary surface’s electric field \( E_o \) is \( \mid E_o (r) \mid = \mid \nabla \Phi \mid = \mid \Phi \mid / r^2 \) which gives \( E_o (r) = \Phi_o r / r^2 \). Substitution into (4) with \( E = E_o + E^* \) yields the general equation

\[
\mathbf{r} = -\frac{\mu r}{r^3} + \frac{Z}{m} \left( E^* + \frac{\dot{r}}{c} \times \mathbf{B} \right), \quad (5a)
\]

where \( Z = Z_{Duo} q \) represents the effective total charge of the dust grain. \( E^* \) is any other ambient electric field such as \( E_{SW} \). The term levitation arises from the fact that whenever \( \Phi_o = GMm / Z \) gravitation is cancelled out.

**Conclusion:** The introduction by Lorentz of motionally induced electric fields as necessary consequences of the relativity of charge in motion plays an important role in the MHD behavior 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 \textit{in situ} measurement of the scalar electrostatic levitation potential \( \Phi \). The commonplace assumption of Equation (4) will always give an incorrect result when the surface potential \( \Phi (\hat{r}) \neq 0 \).