The Principle of Planetary Unipolar Generators

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All planetary bodies are presumably exposed to the direct blast of the solar wind, with the exception of the moon when buried in the geomagnetic tail, and perhaps the outermost planets if the ordered solar wind terminates inside their orbits. A fundamental consequence of this exposure is the existence of a motional electric field $\vec{E}_m$ in the comoving frame of the planet. The existence of such an electric field has the consequence that planetary bodies, where the solar wind can reach the surface, will polarize. The tendency to deposit polarization charges at the poles of the planet is a consequence of the requirement that the interior of conducting bodies can support no electrostatic field.

In the idealized, time independent case where the solar wind parameters are taken as independent of time, the net field, $\vec{E}_m + \vec{E}_p$, where $\vec{E}_p$ is the polarization field, tends to zero provided that the polarization charges cannot leak off into the neighboring plasma. The statement that the body is conducting is an adequate approximation for most planetary matter. The definition is based upon the charge relaxation time, $\tau$, where

$$\vec{E}_p = (1 - e^{-t/\tau})\, \vec{E}'_p \quad ; \quad \tau = \epsilon/\sigma \qquad (1)$$

$\vec{E}'_p$ is the final polarization field, $\vec{E}_p$ the polarization field at time, $t$, $\sigma$ the bulk electrical conductivity of the planetary matter and $\epsilon$ the specific inductive capacity. The time, $t$, is small compared to usual time scales of interest. Thus the approximation is reasonable.

The problem posed becomes interesting when polarization charges are permitted to leak off into the plasma, for then a steady state current will flow. The system constitutes a unipolar generator in series with the plasma and the body of the planet (Sonett and Colburn, 1967a). The dominant impedance in the path determines the current magnitude. If the plasma is assumed to have conductivity large compared to the planetary body, then the impedance of the latter determines the current.

The effect of such a current system is the establishment of a self-exited magnetic field about the body due to the flow of the unipolar current system. One additional assumption is required for the system to function. The plasma which contacts the surface is wholly adsorbed, neutralized by electron pickup, and the particle re-emitted as a neutral at the characteristic temperature of the surface according to an early model of Gold (1966).

In the Gold model the solar wind was thought to impact upon the surface of the moon and the interplanetary magnetic field diffused through the interior. The requirement that the gas be adsorbed permitted the plasma to be decoupled at the surface so as to remove it from consideration in the calculation of body forces. This model was essentially hydromagnetic in character. The model of this paper is electromagnetically consistent with it and permits the calculation of the current magnitude as well as establish the properties of the planet as a unipolar electrical generator.

It is easy to show that the unipolar current system for uniform and time independent solar wind parameters requires that the current system close wholly through the exterior plasma. In the comoving frame $\dot{B} = 0$ and therefore all electric fields are curl-free. Further they are uniform throughout the planet for the homogeneous case. Even for the inhomogeneous case the current system can be shown to require external closure.

Establishment of the unipolar magnetic field means that a back pressure will develop which tends to retard the action of the solar wind in forcing field into the planet. Thus the net electric field which is generated is reduced. In this manner the mechanism tends to saturation. For a homogeneous planet at the distance of the moon from the sun and for the present epoch solar wind, it is possible to show that the current in the lowest mode (see Eqs. 4a, b) cannot become greater than several times $10^5$ amperes.

For the requirement that the field be curl-free and for the reasonable assumption that no current sources or sinks are present in the planet other than the seat of the emf, the current divergence

$$\nabla \cdot j = 0 \tag{2}$$

Together with the curl-free electric field eq. 2 transforms into the fundamental equation for the unipolar potential distribution within the planet becomes

$$\sigma \nabla^2 \Phi + \nabla \sigma \cdot \nabla \Phi = 0 \tag{3}$$

For a homogeneous body, $\sigma$ = const, and eq. 3 reduces to Laplace's equation. A similar condition ensues when $\nabla \sigma \perp \nabla \Phi$. Since the most reasonable source of variable conductivity lies in thermal gradients, it is likely that $\sigma = \sigma(r)$ alone. Then eq. 3 is separable, with solutions of the form

$$\frac{d}{dr}\left(r^2 \frac{dR}{dr}\right) + \frac{r^2}{\sigma}\frac{dR}{dr}\frac{d\sigma}{dr} - n\,(n+1)\,R = 0 \tag{4a}$$

$$\frac{d}{d\mu}\left[(1-\mu^2)\frac{d\Theta}{d\mu}\right] + n\,(n+1)\,\Theta = 0 \tag{4b}$$

where $\mu = \cos\theta$.

For the specific form given for $\vec{E}_m$, only odd values of n, i.e. n = 1, 3, 5, . . . are permitted since $\vec{E}_m$ is antisymmetric. Eqs. 4a and 4b define the field in the interior of a radially inhomogeneous planet such as a hot moon.

For the case above, the dominant impedance in specifying the magnitude of the current is the crustal layer of the body since it is coolest. The current is critically dependent upon the exact form of the crustal thermal profile and the corresponding conductivity profile in the vicinity of the surface. We have correspondingly calculated the electric field profile in the interior of the moon for a radiogenically heated model (Fricker, Reynolds, and Summers, 1967) and find the major drop in potential across the surface layers as expected from the earlier statement that the highest impedance dominates the circuit current. The electric field for the $P_1$ solution to Eqs. 4a, 4b is shown in Fig. 1.

The conclusions drawn from the above discussion can be applied to a variety of planetary bodies and the results are consistent with hydromagnetic theory (Sonett and Colburn, 1967b). The limitation upon the current magnitude for a planet lacking a magnetosphere but containing an insulating atmosphere is determined by the insulating properties of the atmosphere itself. Planets with internally dynamo driven magnetospheres cannot easily be included in our model since the solar wind is essentially completely deviated to the flanks of the body. In the grossest generalization the concept still applies but provides little information of interest and it is as easy to retain the hydromagnetic analogy.

Asteroids, the moon, Mercury, and perhaps some planetary satellites are prime candidates for examination using the principle of the unipolar generator. In the event of sufficient planetary conductivity a large fraction of the flow field of the solar wind will be deviated to the limbs. A shock wave is likely and additional structure on the downstream side of the planet perhaps approximating a magnetohydrodynamic wake. As the conductivity grows, the body becomes a more solid obstacle to the impact of the solar wind. In the other limit of a nearly insulating body, with the proviso that the impacting plasma is adsorbed in the manner described earlier, the planet will be transparent electrically to the solar wind, and the only effect aside from diamagnetism will be to form a geometric plasma void on the downstream side of the body. The magnetic field will pass through the body unimpeded since no current system is set up and back pressure upon the solar wind cannot develop.

## REFERENCES

Sonett, C. P. and D. S. Colburn, Establishment of a Lunar Unipolar Generator and Associated Shock and Wake by the Solar Wind, submitted to Journal of Geophysical Research (1967).

Sonett, C. P. and D. S. Colburn, Planetary Unipolar Generators, to be submitted to Earth and Planetary Interiors (1967).

Gold, T., The Magnetosphere of the Moon, in The Solar Wind, ed. R. J. Mackin and M. Neugebauer, Pergamon Press (1966).

Fricker, P. E., R. T. Reynolds, and A. L. Summers, On the Thermal History of the Moon, J. Geophys. Res., 72, 2649-2663 (1967).

FIGURE TITLE

Fig. 1. The planetary electric field for a moon with a typical radiogenic thermal profile with convection (Model 7 of Fricker et al., 1967). The customary thermal profile is modified by specifying the surface temperature, which defines the surface conductivity, one of the boundary conditions for equations 4. The distance scale is normalized to the lunar radius. A strong polar dependence of the electric field appears, and the radial dependence shows that the bulk of the potential drop is in the first few hundred kilometers beneath the surface. The motional field assumed is 2 mV/m. Other values yield similar results by scaling.

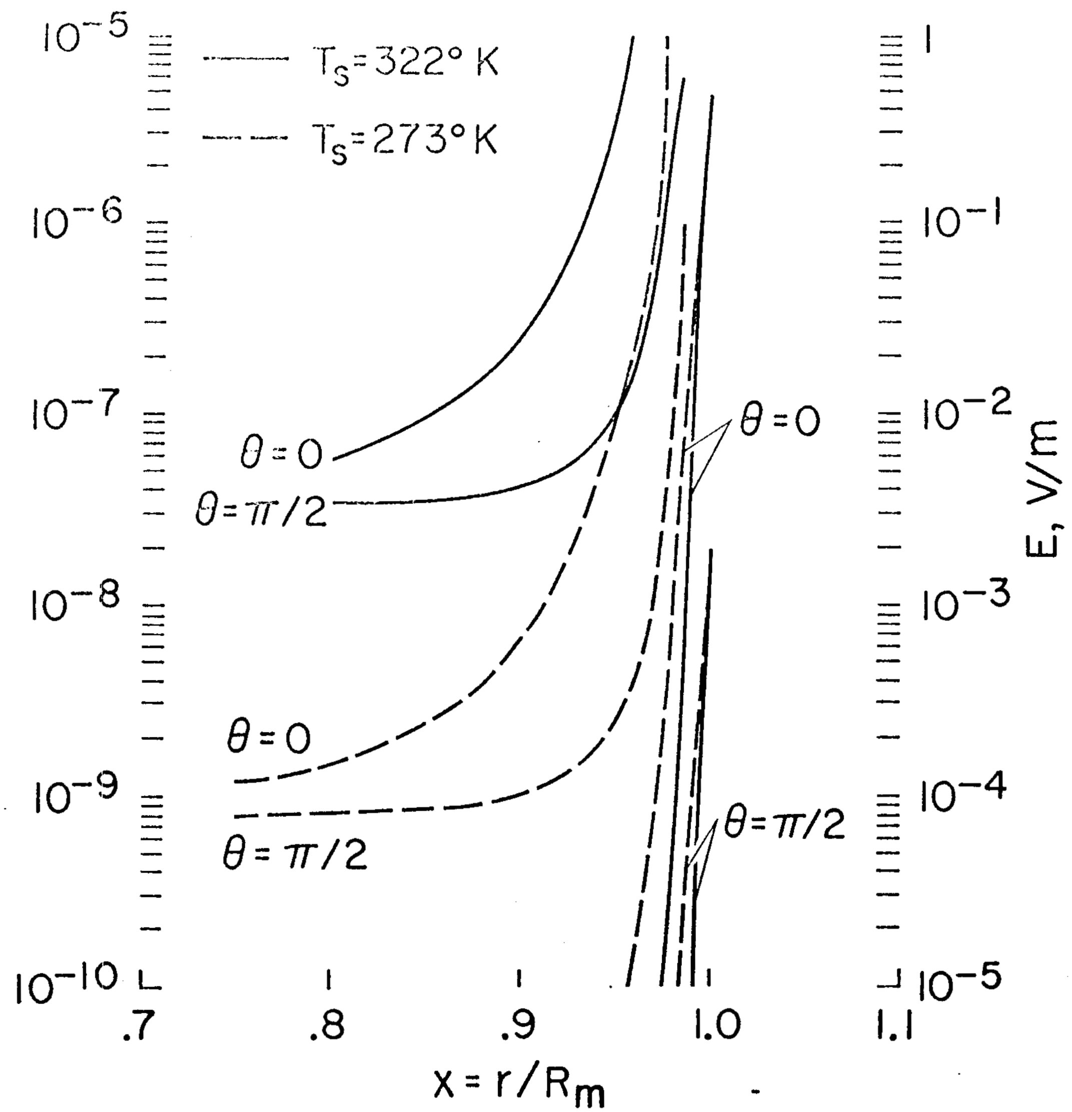


Figure 1.

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