DEEP MAGNETIC SOUNDING OF THE MOON IN THE GEOMAGNETIC TAIL AND PLASMA SHEET, L. L. Hood and G. Schubert, Dept. of Earth & Space Sciences, Univ. of Calif., Los Angeles, CA 90024.

The influence of the external plasma environment on the lunar global electromagnetic response to time-dependent magnetic fluctuations occurring when the moon is in the geomagnetic tail lobes and plasma sheet has been demonstrated [1]. It also appears, however, that when care is taken to select only those transient events occurring in the lobes at times when plasma densities are minimal, low-frequency vacuum response theory may provide an adequate approximation to the lunar response [2]. A magnetohydrodynamic (MHD) response theory which is valid at all relevant frequencies within a cold, nearly static, highly conducting plasma medium of arbitrary density is needed to explain both the observed plasma influence and the quasi-vacuum behavior.

Here we present such a theory for the important class of magnetic field transients which represent time variations in a spatially uniform ambient magnetic field. This type of transient occurs, for example, when the moon crosses the neutral sheet and the entire body simultaneously experiences a step or steep ramp change in the geomagnetic tail field.

From the linearized MHD equations [3], it is possible, in the cold plasma or "low β" limit, to derive the following equation for the magnetic perturbation $\underline{b}$

$$\nabla \times \left\{ \left((\nabla \times \underline{b}) \times \hat{\underline{e}}_o \right) \times \hat{\underline{e}}_o \right\} + k_A^2 \, \underline{b} = 0 \qquad (1)$$

where $\hat{\underline{e}}_o$ is a unit vector in the direction of a uniform ambient magnetic field $\underline{B}_o$ ($|b| << |\underline{B}_o|$) and k_A is the ratio of the circular frequency ω to the Alfvén speed v_A. By introducing a vector potential $\underline{A}$ in the gauge for which the scalar potential $\Phi(\underline{r},t) = 0$, we can write the nagnetic and electric perturbations as

$$\underline{b} = \nabla \times \underline{A} \quad , \qquad (2)$$

$$\underline{E} = -\frac{1}{c}\frac{\partial \underline{A}}{\partial t} \quad , \qquad (3)$$

and it follows that $\underline{A} \cdot \hat{\underline{e}}_o = 0$. Substituting (2) into (1) we find, except for the gradient of another arbitrary scalar function which we choose to be zero, that

$$\nabla^2 \underline{A} - \nabla_\perp (\nabla \cdot \underline{A}) + k_A^2 \, \underline{A} = 0 \quad , \qquad (4)$$

where the $\nabla_\perp$ is the component of ∇ perpendicular to the ambient magnetic field direction. In vacuum, $\underline{A}$ satisfies the vector Helmholtz equation with $k_v = \omega/c$ (c is the speed of light). Since the second term of (4) does not vanish in general, the external MHD response is fundamentally different from the electromagnetic one. However, when the input magnetic field perturbation is parallel to $\underline{B}_o$, then electrical currents are azimuthal about $\hat{\underline{e}}_o$, and

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$$\underline{A} = A_\phi \hat{\underline{\phi}} \quad . \qquad (5)$$

ϕ is the angular coordinate azimuthal about $\hat{\underline{e}}_o$, $\hat{\underline{\phi}}$ is the associated unit vector, and by symmetry,

$$\nabla \cdot \underline{A} = \frac{\partial}{\partial \phi} A_\phi = 0 \quad . \qquad (6)$$

For this physically important situation, (4) reduces to

$$(\nabla^2 + k_A^2)\underline{A} = 0 \quad , \qquad (7)$$

i.e., the vector Helmholtz equation for which analytic solutions are well known. In this case, the MHD response is identical to the electromagnetic one with k_A replacing k_v.

For magnetic field variations of the form $\underline{b} = b(t)\hat{\underline{e}}_o$, the term $k_A^2 \underline{A}$ in (7) represents the effect of the plasma on the externally induced magnetic field, while, for most frequencies of interest, the corresponding term $k_v^2 \underline{A}$ has a negligible effect on the vacuum response. At sufficiently low frequencies, when $k_A^2 \underline{A}$ is very small, the MHD response is indistinguishable from the vacuum one. However, at higher frequencies, $k_A^2 \underline{A}$ becomes important and plasma effects enter to an extent determined by the frequency and the prevailing Alfvén speed

$$v_A = B_o / \sqrt{4\pi\rho_o} \quad , \qquad (8)$$

where ρ_o is the plasma density.

We will present the time varying MHD response of the moon to step and ramp changes in the magnitude of the geomagnetic tail lobe field for different values of the Alfvén velocity and lunar electrical conductivity. A comparison with the vacuum response will provide a quantitative assessment of the importance of plasma. The theory presented here provides a rigorous basis for inferring both lunar electrical conductivity and plasma density from transients in the tail lobe magnetic field.

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