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PREFACE

The study reported here is an attempt to increase the understanding of the lunar environment. It may increase our knowledge of the lunar atmosphere and of parameters of possible interest to radio communications and to studies of the lunar surface made with radio techniques. It is part of a series of studies on particles and fields supported under Contract NASr-21(05) by the National Aeronautics and Space Administration.

ABSTRACT

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The effects of interplanetary magnetic fields on the flow of plasma around the moon are considered. If the moon possesses a negligible magnetic field, and if the conductivity of the moon is not appreciably less than 10^6 sec^{-1} in Gaussian units, a crude analysis indicates that most of the solar wind is deflected around the moon and only a small fraction actually strikes the lunar surface. Consequences for recent models of the lunar atmosphere are briefly discussed.

Although the lunar atmosphere and the lunar magnetic field have long been a subject of speculation and analysis, only recently has the existence of the solar wind been established and its effects on the moon considered. Gold (1962; 1964) has pointed out that the interaction of interplanetary electric and magnetic fields with the moon has many interesting consequences. In this paper an attempt is made to estimate quantitatively the effects of magnetic fields in deflecting the solar wind around the moon. It is concluded that even if the moon possesses no intrinsic magnetic field similar to that of the earth, fields induced by the solar wind deflect most of the plasma around the moon, allowing only a small fraction to strike the lunar surface.

Consider first the possibility that the moon may possess an intrinsic dipole magnetic field strong enough to turn aside the solar wind before it strikes the lunar surface. In this event the flow around the moon should be analogous to that around the earth's magnetosphere. Within the lunar magnetosphere a tenuous classical atmosphere and ionosphere would be able to develop, as discussed by Vestine (1958). However, the observations by the second Soviet cosmic rocket, placing an upper limit of less than 100γ on the surface field intensity (Dolginov, et al., 1960), impose very stringent constraints on any dipole field. For example, it places a small upper limit on the radius of any lunar magnetosphere. The recent observations (Ness, Scearce, and Seek, 1964) indicate that the magnetospheric field of the earth just inside the magnetopause is about 40γ, approximately half of which is due to the earth's dipole field and half of which is caused by currents at the magnetopause. Assuming the lunar field configuration to be essentially the same, and remembering that the dipole field intensity decreases as the inverse cube of the radius, we can obtain an upper bound on the radius of the lunar magnetosphere by requiring the dipole field to be less than 100γ at the surface of the moon and 20γ at the magnetopause. This gives R(magnetopause) ≤ 1.7 R(moon). Lunar surface luminescence, which is apparently related to solar activity (Kopal and Rackham, 1964), might argue against the existence of such a magnetosphere, although it is possible that the magnetic field is blown away or pushed into the moon during periods of intense solar activity, allowing particles to strike the surface. Until more detailed observations are obtained, such a dipole field model must remain a definite possibility.

The more interesting possibility is that the moon possess a negligible intrinsic magnetic field, the field associated with the moon being induced by the interplanetary electric and magnetic fields. Although a detailed model of such a situation must depend on complicated phenomena at the lunar surface, some general conclusions concerning the flow may be drawn independent of such detailed boundary conditions. It is argued below that, even with conservative estimates of the conductivity of the moon, only a small percentage of the solar wind (or associated magnetic field) actually impinges on the lunar surface, the remainder being deflected around the moon.

The moon may be regarded as a conducting body immersed in the solar wind, the interaction of which with the solar wind and its associated fields is determined by processes occurring at the surface and by the induction and decay of electric currents in the interior.

If the conductivity of the moon were precisely zero, then the surface effects themselves would determine the nature of the interaction since there would then be no magnetic effects in the interior. The possible surface effects are many and mixed. Incident ions may be neutralized with varying degrees of efficiency or may be 100 per cent reflected. The high mobility of electrons may result in surface electric fields. For the present, though, it is sufficient to note that perfect neutralization of all ions incident on the surface of the moon probably gives an upper bound on the rate that the ions may strike the moon, for the current set up by reflected ions enhances the external magnetic field, tending to deflect particles away from the surface.

The finite conductivity of the interior of the moon impedes the magnetic field lines as they pass through the moon. Magnetic fields in uniform conducting media obey the familiar diffusion equation, which may be written in Gaussian units as

$$\nabla^2 H - \frac{4\pi\sigma}{c^2} \frac{\partial H}{\partial t} = 0 \qquad (1)$$

(e.g., Landau and Lifshitz, 1960, Chapter VII). Here σ is the conductivity of the medium, c is the velocity of light, and μ the magnetic permeability has been taken to be unity. Equation (1) is a diffusion equation with diffusion constant $c^2/4\pi\sigma$; one can visualize it as giving the rate of diffusion of field lines through the medium. There are several ways of showing that in the moon the diffusivity is so small that most of the magnetic field lines convected to the moon by the solar wind simply slip around the moon instead of passing through it.

We consider first a model in which a steady solar wind with velocity $\mathbf{v}_w$ and an associated magnetic field $\mathbf{B}_w$ impinge on the moon without being deflected. The electric field is given by $\mathbf{E} = - \mathbf{v}_w \times \mathbf{B}_w/c$, so the Poynting vector $\mathbf{S} = \mathbf{v}_n \frac{B_w^2}{4\pi}$, where $\mathbf{v}_n$ is the component of $\mathbf{v}_w$ normal to $\mathbf{B}_w$. Thus the undeflected solar wind convects S ergs cm^{-2} sec^{-1} onto the moon. The order of magnitude of the diffusion velocity of the magnetic field inside the moon obtained from Eq. (1) is $v_D \simeq \frac{c^2}{8\pi\sigma R_M}$, where R_M is the lunar radius. The energy flux is then of the order of $v_D\, B_M^2/4\pi$, where B_M is an average interior magnetic field. To maintain a steady state, therefore, we require that very approximately

$$v_n \frac{B_w^2}{4\pi} \simeq \frac{c^2}{8\pi\sigma R_M} \frac{B_M^2}{4\pi} \tag{2}$$

or, for a nominal solar wind velocity of 5×10^7 cm^2 sec^{-1} (Snyder and Neugebauer, 1964)

$$\left(\frac{B_m}{B_w}\right)^2 \simeq 10^{-3}\,\sigma \quad . \tag{3}$$

Although observational evidence is meager, a surface conductivity of a few times 10^6 sec^{-1} appears to be a reasonable estimate. Radar observations of the moon yield values of a few times 10^6 sec^{-1} (Senior, Siegel, and Giraud, 1962), and terrestrial crustal rocks tend to have conductivities greater than about 10^6 sec^{-1} (Fleming, 1939, p. 288). Since σ is expected to increase with depth, a value of 10^{-6} sec^{-1} will provide a lower bound and we conclude that $B_M/B_w \gtrsim 30$ for this model.

Now, although Eq. (3) is certainly not reliable to more than a factor of 5, or perhaps 10, it is probable that B_M is more than a factor of 10 larger than B_w. Since the motion of the magnetic field is governed by a diffusion equation, it is clear that the field will decrease away from the sunward surface of the moon. Thus if B_{MS} is the field at the surface, $B_{MS} > B_w$. Recent observations have established that the interplanetary magnetic field intensity B_w is normally about $5\gamma (5 \times 10^{-5}$ Gauss), and we may conclude that this model requires a field of the order of or somewhat greater than 100γ at the lunar surface. This is probably inconsistent with the Soviet observations indicating that $B_{MS} \lesssim 100\gamma$ (Dolginov, et al., 1960) and is, furthermore, sufficient to cause substantial deflection of the solar plasma, in contradiction to the assumed model. Therefore if the electrical conductivity of the moon is not much less than 10^6 sec^{-1}, it is unlikely that the solar wind flows onto the lunar surface undeflected.

The magnetic field near the subsolar point will tend to build up to a value which is sufficient to deflect much of the solar wind and its associated magnetic field around the moon. If the solar wind velocity were less than the Alfvén velocity, the flow would simply adjust itself so that some of the plasma flowed around the moon. Since the solar wind velocity is actually several times the Alfvén velocity, the situation is similar to supersonic flow in a fluid, so something analogous to the standing bow shock of the earth must be set up. Behind the shock the plasma adjusts itself to flow around the moon. If the large-scale aspects of this flow are still assumed to satisfy $\underset{\sim}{E} = - \frac{\underset{\sim}{v} \times \underset{\sim}{B}}{c}$, we can obtain a crude upper bound on the ratio Q of the amount of plasma actually striking the lunar surface to the amount that would strike if the flow were undeflected. From Eqs. (2) and (3) one readily obtains

$$Q \lesssim \frac{10^3}{\sigma} \left(\frac{B_{MS}}{B_w} \right)^2 \quad . \tag{4}$$

Pressure balance and momentum conservation require that if any particles are to strike the lunar surface, B_{MS} satisfy

$$\frac{B_{MS}^2}{8\pi} < n_w m_p v_w^2 \quad , \tag{5}$$

where n_w is the solar wind proton density and m_p is the proton mass. Nominal solar wind parameters are $n_w \sim 5 \text{ cm}^{-3}$, $v_w \sim 5 \times 10^7 \text{ cm sec}^{-1}$ and $B_w \simeq 5\gamma = 5 \times 10^{-5}$ Gauss (Snyder and Neugebauer, 1964; Ness, Scearce, and Seek, 1964). This yields $B_{MS} \lesssim 50\gamma$ and, if $\sigma \gtrsim 10^6 \text{ sec}^{-1}$, $Q \lesssim 0.1$. It is likely that the actual value of Q is substantially less than this crude upper bound.

The analysis indicates, therefore, that if the conductivity of the moon is not much less than 10^6 sec^{-1}, most of the solar plasma flows around the moon. The flow of plasma is expected to be similar in many respects to the flow of solar wind around the earth's magnetosphere. In the case of the earth, the fields outside the magnetosphere are seldom in excess of 30--50γ. The same would be expected for the moon, so this model is consistent with the Soviet magnetometer results mentioned above, which preclude fields in excess of 100γ.

Several authors have considered the effects of the solar wind on a lunar atmosphere, concluding that if the solar wind is free to penetrate to the surface of the moon, accretion and removal by the wind dominate the evolution of the atmosphere (e.g., Herring and Licht, 1960; Weil and Barasch, 1963; Bernstein, *et al.*, 1964; Hinton and Taeusch, 1964; and Michel, 1964). Michel (1964) also considered a potential flow model in which all of the solar wind is deflected around the moon. He concluded that the accretion of plasma is unimportant but that attenuation by the solar wind is still important. In the light of the present analysis it is likely that the latter model is more nearly correct, although there apparently is no physical basis for the assumption of potential flow.

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