Permanent Lunar Surface Magnetism and Its Deflection of the Solar Wind

Abstract. *Magnetic compressions intermittently observed outside the lunar wake in the solar wind may be limb shocks caused by the presence of local regions of permanent magnetism on the lunar limb. Observable compression would be due to regions of length scale (radius) at least as great as several tens of kilometers and field strength* $\gtrsim$ *10 gammas. Thousands of such regions might exist on the lunar surface. The steady magnetic field measured at the Apollo 12 site probably has length scale* $\lesssim$ *10 kilometers and probably does not produce an observable limb shock.*

Recent plasma and magnetic observations from the lunar-orbiting satellite Explorer 35 have established the principal features of the large-scale interaction between the solar wind and the moon. Specifically, it has been established that the moon absorbs incident solar-wind particles without significantly modifying the upstream flow, that a cavity containing enhanced magnetic field extends at least 5 R_M (lunar radii) downstream of the moon, and that between this diamagnetic cavity (or umbra) and the unperturbed downstream wind is a region of reduced magnetic field and plasma flux, sometimes called the penumbra (*1*). Outside the latter region a narrow region of magnetic enhancement is sometimes found (*2*); such a feature, which we shall call an "outer compression," is clearly seen on only a small fraction (< 10 percent) of orbital passes; it has a measured amplitude that ranges from a few tenths to several gammas (1 gamma = 10^{-5} gauss).

It is generally agreed that the outer compressions are caused by some deflection of the solar wind by the lunar limb. The compression is usually ascribed to a weak limb shock (*3, 4*), although the details and terminology vary somewhat from model to model.

The cause of the outer compressions is not known at present. Possible explanations can be placed into two classes: (i) those that suppose the deflection to be caused by the simple presence of the lunar limb, and (ii) those that suppose the deflection to be caused by some special feature or features of the limb. Examples of the former explanation include deflection due to currents flowing through the lunar interior (*4*) and deflection due to plasma turbulence in the steep gradients of the boundary sheath between the limb and the solar wind. Examples of the second kind of explanation include deflection induced by the presence of electrically conducting "islands" in the lunar crust (*5*), variable thickness of the moon's insulating crust (*6*), and other local variations in the electromagnetic properties of the lunar surface. Because the outer compressions are detected intermittently and because most of them occur when specific regions of the lunar surface (mostly in the highlands) are at the limb (*6*), explanations of the first class should probably be dismissed. We wish to discuss in some detail one of the models of the source of the deflection: namely, deflection of the flow by magnetic fields from local regions of relatively strong permanent magnetism on the lunar surface (*6*). In this report we comment on the possible distribution and strength of such sources and the way in which they would be expected to interact with the solar wind.

The measurement of a steady magnetic field of 38 ± 3 gammas at the site of the Apollo 12 landing (*7*) indicates that there is at least one region of permanent magnetism on the lunar surface. From null measurements of field-strength gradient at the Apollo 12 site and of permanent lunar field at periselene of Explorer 35 while it was in the geomagnetic tail (*7*), it was concluded that if this source is taken to be dipolar and lying near the surface at distance L from the magnetometer, then it may be characterized by $0.2 \lesssim L \lesssim 200$ km, and equivalent dipole moment in the range $1.4 \times 10^9 \lesssim M \lesssim 1 \times 10^{18}$ gauss-cm³. The effective dipole is characterized by

$$ML^{-3} \sim 2 \times 10^{11} \qquad (1)$$

where M is in gauss-cubic-centimeters and L is in kilometers. Since at distances from the source much larger than L the field due to the source would not be clearly discernible, L as given by Eq. 1 is also the characteristic size of the region of locally enhanced magnetic field that contains the Apollo 12 site.

It is unlikely that such a region of permanent magnetism ("magcon") is unique [although the possibility of an isolated magnetic field anomaly has been discussed before (*8*)]. One can make a crude estimate of an upper limit on the number of "magcons" on the lunar surface in the following way: Suppose that on the lunar surface there are N magcons similar to the magcon at the Apollo 12 site and that they possess magnetic moments of magnitude M and length scales L. (For definiteness, consider a magcon to be a sphere of radius L.) The total area occupied by the magcons must be less than (or comparable to) the surface area of the moon:

$$NL^2 \lesssim 4R_M^2 \simeq 10^7 \text{ km}^2 \qquad (2)$$

Further, the net magnetic moment due to the magcons must not be greater than the upper limit determined by Explorer 35 observations. In the extreme case, in which all the dipole moments are aligned, this criterion is roughly

$$NM \lesssim 10^{20} \text{ gauss-cm}^3 \qquad (3a)$$

and, in the opposite extreme case in which the dipole moments are randomly oriented, the criterion is

$$N^{1/2}M \lesssim 10^{20} \text{ gauss-cm}^3 \qquad (3b)$$

When the above limits on M and L are considered, Eq. 2 is a stronger restriction than Eq. 3, whether the dipoles are aligned or random, except for $L \gtrsim$ 100 km. Hence, if $L \sim 100$ km for the magcon, then $N \lesssim 10^3$, and if $L \sim 10$ km, then $N \lesssim 6 \times 10^4$. Although the above numbers should not be taken too seriously, they do indicate that it is plausible for the lunar surface to contain several hundred magcons of scale $L \sim 100$ km and many thousands of magcons of smaller scale. This assertion does not depend on any assumption about the relative orientation of the magcons. Future low-orbiting spacecraft and manned missions could provide definite information on the size, orientation, and strength distribution of magcons.

Next we consider the interaction between the solar wind and a magcon. The nature of this interaction would depend on the size L and the field intensity B, as well as whether the magcon is on the limb or on the sunward face of the moon. Consider first the case in which the magcon is on the sunward face. A test electron entering a 35-gamma field at the solar wind velocity is turned around in a distance of about 50 m, and the Debye length of the solar wind is of the order of 10 m; hence, for L greater than a few tens of meters, the solar wind would interact with the magcon as a neutral plasma rather than as a flux of independent charged particles. For L larger than some critical value L_0, the magcon field would be compressed until its magnetic pressure balances the dynamic pressure of the solar wind and stands off the flow; the magnitude of the compressed field would be in the range of 45 to 60 gammas for most solar-wind conditions. The value L_0 is a measure of the thickness of the interaction region. We take $L_0 = A\lambda$, where $\lambda = c/\omega_{p-}$ is the electron inertial length (c is the speed of light, and ω_{p-} is the electron frequency), and $A \lessapprox 5$. This length is the interaction distance between a streaming plasma and a magnetic field in a hypothetical laminar flow (*9*) and is comparable to the shock thickness predicted by many collisionless shock theories for solar-wind conditions (*10*). Observation indicates that this length is characteristic of the thickness of the earth's bow shock (*11*).

For typical solar-wind conditions, $L_0 \lessapprox 10$ km. We expect that if $L \ll L_0$, the steady field at the magcon would be unaffected on passage from the earth's magnetic tail into the solar wind, whereas if $L \gg L_0$, this field would be compressed and would stand off the solar-wind flow, possibly forming a local shock.

For the case of the steady 38-gamma field observed at the Apollo 12 site, one would expect considerable compression on passage from the geomagnetic tail into the solar wind if $L \gtrapprox L_0$. It appears that this field is not enhanced more than a few gammas during this transition (*12*), so that apparently the scale L of this region of steady magnetism is not more than about 10 km.

Next, consider the case in which the magcon is on the lunar limb. Then it can cause a deflection of the solar wind in at least two ways. First, if the scale $L \gtrapprox L_0$, the pressure of the compressed magcon magnetic field will turn the flow away from the moon. Second, the region of interaction will necessarily be strongly inhomogeneous and will contain strong currents; these properties almost certainly will generate plasma noise over a wide frequency range through various plasma instabilities. If this occurs, the magcon will act as a local source of plasma turbulence; particles deflected toward the lunar surface will be absorbed, so that the net effect of such a region would be to deflect the plasma flow away from the lunar surface. Whatever the details of the interaction are, we expect that at some distance from the limb the presence of a magcon is manifested in a hydromagnetic shock wave, whose strength and shape are determined by ambient solar wind conditions and some quantity or quantities characteristic of the magcon. However, it is clear that, if we observe the shock sufficiently far from its source, it must appear as a Mach wave of vanishing amplitude. Thus, the strength of the disturbance observed by Explorer 35 depends not only on the solar wind and magcon properties but also on the distance of the spacecraft from the magcon.

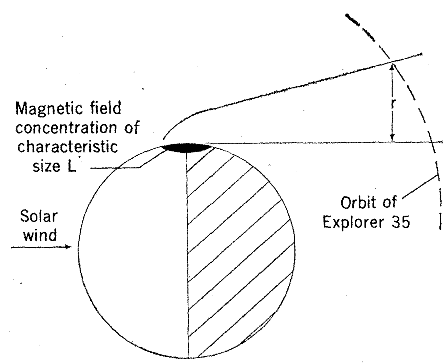

Fig. 1. Trace of the limb shock due to a region of permanent magnetic field on the plane of the orbit of Explorer 35.

In order to analyze the disturbance far from the magcon, we replace it by an "equivalent" solid body, which produces the same local solar wind deflection and has a length equal to the scale of the magcon. If the deflection is small, the strength of a gas dynamic shock associated with, but far from, such a body in a supersonic flow (as measured by the relative pressure jump $\Delta p/p_\infty$) diminishes in proportion to $(r/L)^{-3/4}$, where r is the distance from the body projected onto a plane perpendicular to the undisturbed flow (see Fig. 1) (*13*). The density jump $h = \Delta\rho/\rho_\infty$ then satisfies the relation (for the ratio of specific heats $= 5/3$) $(3/h + 1)\ (L/r)^{3/4} = 3/h_0 - 1$, where h_0 is the density jump near the body, assumed to be of order 1 or less. This relation is true for the hydromagnetic case if $\beta \gg 1$ (β = gas pressure/magnetic pressure); for purposes of illustration we shall use it generally.

For the compression waves observed by Explorer 35, the relative magnetic field jump is approximately equal to the relative density jump (*3, 4*) with $h = 0.2$ a typical value. Compression waves are observed at values of r up to 2000 km. Adopting a representative value of $r = 750$ km, we find $(3/h_0 - 1)^{-1}L^{3/4} = 9$. Therefore, for $h_0 = O(1)$, L is at least several times 10 km. For $h_0 \ll 1$, $L \sim 80\ h_0^{-4/3}$.

If from the Explorer 35 data we take values of h and r associated with one localized region on the moon's surface (instead of taking mean values for all the observations), $h_0(L)$ can be estimated. We take nine observations associated with the region at 13° to 25°S and 128° to 144°E (selenographic coordinates). From these observations we find $h_0(L) = 3/[(0.0423 \pm 0.0022)L^{3/4} + 1]$. If a measure of L is taken as 5 ± 1.5 degrees of latitude, $L^{3/4} \sim 43.0 \pm 9.7$ and $h_0 \sim 1.1 \pm 0.2$, but we have not ruled out smaller L and different $h_0(L)$, perhaps appropriate to the individual observations.

We note that a compressive disturbance caused by a magcon as small as, say, 10 km would be attenuated by a factor of approximately 25 (for $r = 750$ km). Therefore, if our deduction about the smallness of the magcon at the Apollo 12 site is correct, it should produce no disturbance detectable by Explorer 35.

To summarize, we have argued that the large-scale magnetic compressions intermittently observed in the interplanetary medium just outside the lunar wake may be due to limb shocks caused by the presence of local regions of permanent magnetism (magcons) on the lunar limb. In order to produce a limb shock observable at Explorer 35, a magcon must have a length scale L of at least several tens of kilometers, with a (compressed) field strength $B \gtrapprox 10$ gammas. Such an interaction region should be filled with local plasma turbulence covering a wide range of frequencies; this turbulence might play a major role in the flow deflection associated with the disturbance. Present orbiter data are consistent with the presence of thousands of such magcons, which would cover a sizable fraction of the lunar surface.

However, we also conclude that the only permanent local surface magnetization directly observed to date is of small scale, $L \lessapprox 10$ km. This conclusion is based on the weakness of the compression of this field by the solar wind. Hence, this particular magcon would not be expected to produce an observable limb shock, consistent with the fact that deflections are not clearly associated with this region (*6*).

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Modified Superheating of Purified Water

Abstract. *Purified water, intensively redistilled and allowed to overflow so as to shed residual adsorbate from the container, acquires a limiting thermal sensitivity to additions of long-chain fatty acids and alcohols. Thus two to three molecules of* cis-*13-docosenoic acid supplied for each 1000 molecules of exposed surface of water held quietly at the normal boiling point increases the superheat,* Δt_s, *by 10 percent.*

A clean water surface can play host to very dilute monolayers (*1*) of insoluble substances (*2*) which may then assume a planar gaseous mode (*3*). The lateral pressure between the contaminated surface and a truly clean surface has been estimated by means of the two-dimensional analog of the ideal gas equation:

$$\pi A = kT \qquad (1)$$

where π is the surface pressure, A is the surface area per molecule, k is Boltzmann's constant, and T is the absolute temperature. According to Eq. 1, there would exist a pressure of ~ 1 dyne/cm when one molecule of adsorbate occupies 412 Å^2 of water area at 25°C and a pressure of 0.1 dyne/cm where ~ 4000 Å^2 of water area are available (*4*). The small changes in surface tension associated with a dilute monolayer are known to dampen surface ripples; Garrett and Bullman (*5*) have traced the relation between damping and surface pressure for many insoluble adsorbates down to a fraction of a dyne per centimeter. Jarvis *et al.* (*6*, pp. 41–58 and figure 1, p. 43) have measured the increase in subsurface temperature (relative to that of water with a clean interface) when a dilute monolayer has been applied to shallow pools evaporating into a stream of nitrogen under ambient conditions. Working with shallow layers in the open air at room temperature has natural advantages, hence the century of distinguished researches in this area which continue today (*7, 8*).

The observations we report here concern thermal responses to very small concentrations of surface-active compounds adsorbed from the gas phase onto deep pools of hot water, for example, at the boiling point, with the complete exclusion of foreign gas. This model, which invites attention as compellingly as the shallow pool model, embraces the vessels of domestic experience, the flasks and kettles of the laboratory and chemical plant, and, less directly, the pond and ocean. In a deep vessel of symmetrical proportions the laterally repetitive phenomena of the shallow layer are overridden by

Table 1. Relative thermal responses to additives.

Number of molecules added* (× 10^{-10})	Area of water surface per molecule of additive† (Å^2)	Increase in superheat‡ (%)
	Myristic acid	
1100	12	7
2200	6	16
	Palmitic acid	
98	140	8
490	28	18
	Stearic acid	
18	760	10
88	155	22
	Oleic acid	
18	760	11
89	155	19
	Elaidic acid	
18	760	11
89	155	21
	12-Hydroxystearic acid	
170	80	15
250	54	24
	Methyl ester of 12-hydroxystearic acid	
3.2	4300	12
160	85	40
	Methyl ester of 9, 10-dihydroxystearic acid	
3.0	4500	12
	Behenic acid	
2.9	4600	9
15	930	24
	Erucic acid	
3.0	4600	11
15	920	28
30	460	35
44	310	42
74	180	46
150	92	41
220	62	42
300	46	42
740	18	44
	Brassidic acid	
2.9	4600	11
	Lignoceric acid	
2.7	5000	12
27	500	47
	Nervonic acid	
2.7	5000	13
14	1000	35
	Behenyl alcohol	
31	440	7
150	91	12
	Erucyl alcohol	
150	91	17
	Lignoceryl alcohol	
28	490	9
140	98	21
560	24	35
	Nervonyl alcohol	
28	409	11
140	98	25
	Di-2-ethylhexyl phthalate	
26	530	17
720	19	43
	Antarox 430§	
130	105	22
630	22	41

* Error, ± 5 percent. † On the assumption that all of the adsorbate is uniformly distributed over the 82-cm^2 water surface. ‡ Percent increase in superheat above 0.39° ± 0.02°C. The values in this column are accurate to approximately 10 percent. § Nonylphenoxytri(ethyleneoxy)ethanol.