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HOW TO USE MAGNETIC FIELDS FOR FUN AND PROFIT

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For a variety of reasons all centered around the question of the origin and the subsequent evolution of the Moon, it would be important to have an understanding of how the remanent magnetism observed in the Apollo samples originated and at the same time to understand other manifestations of lunar magnetism obtained by the Explorer 35 lunar orbiter, the Apollo 12 Lunar Surface Magnetometer (LSM), and the Apollo 14 Lunar Portable Magnetometer (LPM).

We discuss first the Explorer 35 results. In the magnetic tail of the earth the magnetosonic velocity is likely about 500-1000 km/sec, whereas the orbital speed of the Moon with respect to the tail field is about 1 km/sec so that electromagnetic interaction effects due to the relative motion are likely very small, and nearly certainly undetectable with present instruments[1]. Thus, the Explorer data can be used to test for a global field, static and free of motional effects. Such tests indicate that a large scale field would have a value of less than about 2 gamma at the lunar surface giving due allowance for orientation and noise in the background field[2]. Recent unpublished tests suggest an even lower value (Mihalov, private communication). That a significant field is absent at the present time has hitherto seemed entirely understandable in terms of dynamo theory for it has long been known that the Moon's density completely excludes the existence of a metallic core of appreciable size. The intrinsic spin rate of the Moon is equal to the orbital rate and thus small; this in itself has cast doubt on the existence of a lunar dynamo. Further, magnetometer data suggest that the Moon's interior is well below the temperature at which such a core could be molten and thermal convection occurring within it[3].

But when attention is directed to smaller scale fields the Moon appears after all to be magnetically a "special object". For several years anomalous increases in the interplanetary magnetic field adjacent to the diamagnetic wave which defines the edges of the plasma cavity behind the Moon have been noted[4,5]. The data show unmistakeable evidence for some kind of interaction of the solar wind with the limb of the Moon. Projection of the disturbances seen at the position of Explorer 35 in orbit upwind towards the surface of the Moon enables the sources to be mapped on the lunar surface. Most of the sources lie in the highlands, preferentially on the far side and tend to cluster within 30 deg. of the lunar equator. These data suggest just above the surface of the Moon there are magnetic field anomalies on a scale (mesoscale) of perhaps 10-100 km very approximately, intermediate between global and the microscale discussed below[6]. Barnes, et al., have discussed these events in terms of a plasma interaction at the solar wind terminator of the Moon and suggest that many such "magcons" are present[7].

Additional evidence of lunar magnetization comes from examination of lunar samples returned to earth. The findings are complex, but a clear indication is present of remanent magnetization both in the basaltic rocks and in breccias[8-13]. Furthermore the Apollo 12 magnetometer disclosed a magnetic field of about 35 gamma in the vicinity of the landing site and the Apollo 14 magnetometer showed a permanent field of about 35 gamma at Cone Crater and 100 gamma at Site A, about 1 kilometer away[14], a definite indication of a microscale for at least some of the field.

Permanent magnetization of the lunar rocks is, in the absence of a lunar dynamo, the only source of a steady field. This is only possible down to a depth of between about 200 km and 800 km dpending on the selenographic thermal gradient range (1° - 4° C/km) assuming the Curie point of pure iron. The data could therefore be explained by the spotty occurrence of such magnetization of the surface. It is, however, important to realize that it is only at the edge of a uniformly magnetized plate or when the intensity of magnetization changes markedly in direction or magnitude that the external magnetic field from the plate approaches $2\pi I$ where I is the intensity of magnetization. The field just outside, but near the center line of a uniformly magnetized disk of radius r and thickness, t, equals $2\pi I\, t/r$ and vanishes everywhere as $r \rightarrow \infty$. Thus, since the lavas in the maria basins, because of low viscosity, seem to have spread, they would, even if extensive, be thought to give fields only locally even though uniformly magnetized. The relative absence of magcons on the maria reflect not that the lavas are unmagnetized, but that they approximate uniform magnetic bodies and cratering, and other subsequent disordering which would tend to expose edges, are relatively unimportant.

By contrast, in the highlands it is less likely that the structure can be approximated by thin plates, uniform in composition, and therefore likely to be uniformly magnetized. Further, the greater density of cratering on the highlands will result in more edge effects. Thus the magnetic fields could be greater over the highlands even though the intensity of magnetization of the highland rocks were the same or even less than that of the lavas in the maria basins. It is also worth noting that in the depths of the lunar crust below the shattered upper layers, the Moon could be uniformly magnetized to 5×10^{-5} emu/gm, of the order of the NMR of the returned lunar basalt samples, and still only produce an external dipole field of 2 gamma at the equator, assuming that the magnetization extended downwards 1/10 of a lunar radius.

Let us now recast the evidence. Basalts and breccias both show fossil magnetism though to be cog enetic with the Rb/Sr "clock" start. Explorer 35 suggests magnetism to be isolated events favoring the highlands which are 1 aeon older than at least some of the maria. Apollo 12 shows a local "spot" in the maria; reasonable arguments indicate this to be very local[7]. There appears to be no evidence for significant global magnetism. The threshold is some 10^{20} cgs and perhaps lower[1]. If the evidence being assembled holds together, then the Moon passed through one or more magnetizing events early in it's history. The principal mechanism for field imprinting is by the material passing through it's Curie temperature in the presence of a background field of order 10^3 gamma. It seems clear that the event(s) is(are) in the time range of 3.2-4.7 aeons ago, at the time that the Moon was an interesting object.

The Explorer data suggests large scale magnetization of basement rock, subsequently heated and/or shattered so that the present field is spotty. The Apollo data suggest a time cogenetic with the 3.2-3.7 aeon ago time span and magnetization of basalts. Thus, the magnetic data is consistent with magmatic episodes on the Moon and entirely consistent with, <u>and requires</u>, other evidence for magmatic activity.

The key issue is the source of the background field and the chronology.

Even such exotic mechanisms as shock insertion of the field require a background magnetic field. There seem to be three genuinely distinct sources for such a field. Suppose first that the sun supplied the background. Assume that there existed no solar wind. Then for the required field at 1 AU, the solar field (assumed dipolar) at the sun would have had a magnitude of order $200^3 \times 10^3$ gamma or 8×10^4 gauss, an unacceptable value. Furthermore, there is no reason to suppose that, in view of the Sun's spectral class, it ever lacked sufficient chromospheric activity needed to provide a solar wind[15]. Also, the evidence for spin damping requires a magnetohydrodynamic wind, at least part of the time[16]. If the solar wind were more recent that the 3.2 aeon time, then some embarassingly large magnetic field episodes might be required for the Sun well after it is supposed to have entered onto the main sequence and become well behaved.

Suppose alternatively that the Parker spiral field geometry prevails over all solar history, admittedly much more chaotic during the pre-main sequence phase, i.e., there was both a solar field and solar wind. It is easy to show that the dependence of the tangential component of the interplanetary field B_t upon solar spin is linear, and of the radial component, B_r, upon distance from the sun is quadratic[17]. Thus a very large interplanetary field can be generated by increasing the solar spin and the solar surface field. These constraints must be made consistent with solar spin down and centrifugal limits[15]. Reasonable models suggest that such large fields might have existed during pre-main sequence times, but probably not 1 aeon after the sun moved onto the track of main line evolution. A very considerable additional problem in generating the required field from the sun is the evidence that the direction of the field switches sign at least twice every solar revolution[18]. For a fast sun this could happen every hour. If this sector structure is a consequence of conservation of div B, then it should be a fundamental property of the Parker geometry. The importance lies in the improbability of imprinting fossil fields into a cooling magma on the Moon with a field which switches sign so often. The problem could be solved by requiring the Sun to have had a quadrupole main field, but this is a very special and artifical requirement.

A second unlikely field source would have been the magnetosphere of the Earth. In this model the Moon executes a classic Gerstenkorn[19] approach with which there are well known difficulties. The remanence seen in the rocks is cogenetic with the Rb/Sr ages, but the age difference of the basalts from Mare Tranquilitatis and Oceanus Procellarum differ by about 500 million years; thus unless an orbital resonance can be supposed to have retained the Moon close to the earth, the proximity of the Moon to the Earth cannot be used to account for the magnetizing field[20].

If the Moon were formed in orbit from a hot Earth atmosphere[21], then the Earth's magnetic field could be responsible, but the chronology of the Apollo rocks tend to suggest that the formation of the Moon preceeded the basalt magnetization by 1 billion years during which the Moon would have retreated from a position close to the Earth.

The third possibility is that the Moon once had an internal magnetic field which it has since lost. This involves postulating that it has an iron core which was above the melting point over 3 billion years ago. If the internal temperature had fallen to below the melting point of iron since then, it would be easy to understand why the magnetic field had disappeared, for the free decay time constant of the core is a few thousand years. It has been argued[22] that in order to account for the marked departure of the Moon from hydrostatic equilibrium and especially the discrepancy between its dynamical and surface ellipticities, thermal convection is occurring in the Moon. As a second degree harmonic density distribution is necessary to cause differences in the lunar moments of inertia, a second harmonic convection current system is then required. As the pressure gradient in the Moon is small, it is likely that the effective viscosity of the interior does not change greatly with depth. Also, the Rayleigh number will not greatly exceed the critical value. Thus, we can apply the theory of marginal stability with some confidence and a core of radius 0.06-0.3 of the lunar radius is required if the occurrence of a second rather than a first or higher harmonic convection pattern is to be explained.

Recent determination of the moment of intertia factors of the Moon (C/Ma^2) by Michael[23] lead to restrictions on the size of the core and a value of 1/5 the lunar radius, i.e., 350 km seems to be the greatest allowable. The magnetic Reynolds number for such a core is about 100 v, where v is the velocity of the convective motion in cm/sec. Thus, velocities of about 0.1 cm/sec. would be required to produce dynamo action as the critical magnetic Reynolds number is about 10. This is an order of magnitude less than in the Earth's core. We have little idea of the heat sources within the Moon, but if these are radioactive, their decay could have caused v to decrease with time. So it is possible that the magnetic Reynolds number could have fallen below the critical value for dynamo action sometime in the last 3400 million years.

It also seems certain that the retreat of the Moon from the Earth has caused a slowing down of its rotation period, for internal damping would surely have kept this equal to the orbital period. Rotation plays an essential role in core dynamics and this decrease could have caused cessation of dynamo action in the Moon.

We have discussed the third possibility last because it seems the easiest to justify, provided that the Moon was endowed with a hot core. Actually, the problem is more complex because of the magnetometer evidence for a low temperature core. If a hot core had existed, then a substantial share of the heat should have been retained, though the small volume shows that such heat distributed over a larger volume of the Moon during the subsequent several billion years would result in a lower present temperature.

In view of the speculative nature of this Comment, one might imagine a dynamo of higher order symmetry having operated in the lunar mantle, but since molten silicates have electrical conductivity several orders of magnitude lower than that for metals, this seems awkward. Computer calculations of accretional heating profiles show that significant residual heat would have existed 1 aeon after formation of the Moon if the initial heat input were significant. The thermal peak drifts inwards about 200-300 kilometers in 1 aeon and the peak value decreases somewhat[24].

The attractiveness of the dynamo hypothesis rests upon the relatively long term operation of the dynamo, sufficient to cover the apparent large time span required by lunar rock melting; eventually the process is damped either by spin down, by cooling to where the magnetic Reynolds number is too low, or both.

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