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Intensity and origin of the ancient lunar magnetic field

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There is now strong evidence that the Moon possessed a magnetic field between 4000 and 3200 Ma ago. The evidence for and origin of this field are discussed, and determinations of its intensity described. It is tentatively concluded that the field decreased from an initial intensity of about 1 G (10^{-4} T) during the above time interval, and the implications of the initial intensity and its decay for the origin of the field are discussed.

Introduction

The application of the techniques of palaeomagnetism to lunar rocks has provided unexpected and interesting results which bear significantly on the history and structure of the Moon. Lunar palaeomagnetism is more restricted in scope than similar terrestrial studies both because of the limited amount of rocks available and because the samples, with one possible exception from the Apollo 15 site, are loose pebbles and fragments taken off the surface or broken off larger surface rocks. This means that the direction of any natural remanent magnetism (n.r.m.) found in the samples cannot be related to a lunar reference system to investigate the nature of an ancient global lunar magnetic field from which the rocks acquired their n.r.m. However, two important aspects of palaeomagnetism can be investigated, namely the existence of a stable component of n.r.m. indicative of the presence of a magnetic field when the rocks were formed, and the intensity of this field; these topics form the subject of this paper. If there is evidence of an ancient lunar magnetic field of internal origin, then the process by which it was generated must be consistent with, and can contribute evidence for, the structure and history of the Moon proposed from other investigations.

Evidence for an ancient lunar magnetic field

Many of the lunar samples are similar to terrestrial lavas, both petrologically and in that they have cooled and solidified from a high temperature (> 1000 °C) on the lunar surface after extrusion. In terrestrial lavas this leads to the acquisition of thermoremanent magnetization (t.r.m.) parallel to the direction of the geomagnetic field at the site at the time of cooling. Thus, on the Moon, if there was a magnetic field present at the time when the lavas were cooling, a fossil record of this field will be preserved as a t.r.m. This t.r.m. is acquired as the rock cools through the Curie temperature of the constituent magnetic minerals; in lunar material iron is the dominant carrier of t.r.m., with a Curie point of about 780 °C, or less if there is some nickel present.

Although the specific intensity of t.r.m. will be low in typical planetary magnetic fields of ~1 G it is stable and should withstand medium or high alternating demagnetizing fields. Also, if the n.r.m. is a t.r.m. acquired from above the Curie point, on heating the rock to successively higher temperatures in zero field the n.r.m. should persist up to or near to the Curie point. These characteristics of t.r.m. have been observed in many lunar rocks. In some instances there is a single, highly stable n.r.m. present (Collinson *et al.* 1972) but more typically there is also evidence of secondary magnetizations of lesser stability which can be removed by alternating field and thermal demagnetization revealing the stable t.r.m. (Strangway *et al.* 1971; Collinson *et al.* 1972, 1973; Pearce *et al.* 1973). Some of these secondary components are acquired in subsequent heating events on the Moon, but many of the very low stability magnetizations (removed in < 30 G) appear to be acquired in the returning spacecraft (Pearce *et al.* 1973).

The above results and other characteristics of the n.r.m. of lunar crystalline rocks strongly suggests that they possess a thermoremanent magnetization acquired in a lunar magnetic field. The lunar breccias have clearly had a more complicated history than the lavas, but many of them show the same evidence of a primary stable n.r.m.

The origin of the ancient lunar magnetic field

The crystallization ages of the rocks returned from the Moon lie between about 4000 and 3200 Ma and the rocks which contain evidence of an ancient lunar field cover this time interval. Thus the lunar field must have existed for this period, which provides a constraint in theories of the field's origin. An early hypothesis that the lunar field was in fact the geomagnetic field at the Moon when the Moon was much nearer to the Earth is inconsistent with the age data, since the Moon is very unlikely to have spent such a period close enough to the Earth to provide a significant field (Sonett & Runcorn 1973). Also, at Roche's limit of about 2.5 Earth radii, the nearest the Moon could have been, the geomagnetic field has decreased by a factor of about 15 and by 100 at 4.5 R_E; recent work (see next section) suggests that the lunar field must have been much greater than the 3000–500 nT implied by these factors. There is no evidence from investigations of the intensity of the ancient geomagnetic field that it was significantly greater at any time in the past (McElhinny 1973).

The solar wind magnetic field, at present about 5 nT at the Moon, would have to be several orders of magnitude greater to magnetize the lunar material to the observed intensity, and another feature which makes it an unlikely source is that the effective field is the small component parallel to the lunar rotation axis, the equatorial component being averaged out over a rotation period.

It is now believed that an internal origin of the field offers fewer difficulties, and recently Runcorn (1975) has related the observational data on the present lunar field of Russell *et al.* (1974) to a theorem involving the external field of a spherical shell magnetized by a field of internal origin. The theorem shows that if the shell is magnetized parallel and proportional in intensity to the magnetizing field at each point then, after removal of the magnetizing field there is zero field external to the magnetized shell.

Two possible mechanisms are currently favoured for an internal origin, the first of which is a dynamo process in a molten conducting lunar core, analogous to that producing the Earth's field. Sometime between 3000 Ma ago and the present the core cooled and the magnetic Reynolds number decreased causing the dynamo action to cease. Recent calculations of the moment of inertia factor of the Moon give 0.3953 ± 0.0045, consistent with an iron core of up to 400 km radius (Kaula *et al.* 1974). Seismic data concerning the central regions of the Moon are sparse; Nakamura *et al.* (1974) quote very tentative evidence (based on one event) for a low velocity central core of up to 360 km radius. Objections have been raised on thermal grounds to the existence of a molten iron core for hundreds of millions of years (Tozer 1972; Brett 1973), although an iron sulphide core at a much lower temperature (< 1000 °C) is a possible alternative, and Levy (1972) considers dynamo action in a lunar core unlikely on theoretical grounds. However, present dynamo theory does not appear to be sufficiently rigorous to reject a lunar dynamo on theory only.

A surface magnetic field associated with a permanently magnetized Moon has been proposed by Runcorn & Urey (1973), the magnetization being acquired by alignment of iron particles during a 'gas sphere' phase of lunar evolution (Urey 1966) in an enhanced interplanetary magnetic field. An alternative process was proposed by Strangway & Sharpe (1974), in which a 'cold' Moon (below the iron Curie point) acquired an isothermal remanent magnetism in the interplanetary field. In both mechanisms, subsequent interior heating above 780 °C removed the magnetization, after surface rocks had acquired thermoremanent magnetization during the rise in temperature associated with the emplacement of the mare basalts.

In distinguishing between dynamo and permanent magnetism hypotheses the intensity of the ancient lunar field and its variation with time are of some significance. Broadly speaking a field arising from permanent magnetism would be expected to be constant during the time period covered by the rocks, or steadily decaying if interior heating is already occurring, whereas a dynamo field might possibly be variable in intensity with the average value constant or decaying. The variability might be associated with reversals of the field, which would, of course, be crucial evidence for the dynamo, but because of the lack of oriented samples reversals cannot be directly detected. Banerjee *et al.* (1974) have studied the n.r.m. of samples taken from a large layered boulder at the Apollo 17 site and found divergent directions of n.r.m. in different layers; a possible explanation is a changing ambient field, but the authors point out that further investigation is necessary before this can be confirmed.

Although the intensity of the field from a dynamo is impossible to estimate, a reasonable upper limit can be obtained in the case of permanent magnetism, based on the lunar iron content and the known magnetic properties of the returned samples.

The intensity of the ancient lunar field

On the assumption that the primary magnetization in lunar rocks is a t.r.m., the intensity of the field in which it was acquired can in principle be determined. One method depends on the proportionality of t.r.m. intensity and ambient field over a range of small fields (about 1 G or less): this is the case whether the t.r.m. is acquired from above the Curie point or in some temperature interval below, and the amount of t.r.m. acquired in the interval will be lost when the rock is heated through the same interval in zero field. Thus, the rock is heated to successively higher temperatures in zero ambient field and the n.r.m. lost in each interval is compared with the t.r.m. gained in a known field (H_p) in the same temperature intervals. The ancient field (H_a) is then given by

$$H_a/H_p = \text{n.r.m. lost/t.r.m. gained}$$

the ratio on the right-hand side being ideally determined over suitable temperature intervals up to the Curie point. Figure 1 shows the results obtained from sample 62235.

Because of difficulties which sometimes arise through heating the samples, an alternative method has been used by Stephenson & Collinson (1974) in which the acquisition of anhysteretic magnetization (a.r.m.) in a known d.c. field is compared with the decay of the n.r.m. during a.f. demagnetization. A.r.m. is acquired by a rock when a small d.c. field is applied in the presence of a much larger alternating field, which decreases from some initial level to zero. A.r.m. has many of the characteristics of t.r.m., in particular proportionality of intensity and applied d.c. field. A palaeointensity determination takes the form

$$H_a/H_p = (\text{n.r.m. lost/a.r.m. gained})/f'$$

the 'lost' and 'gained' referring to an alternating field interval, analogous to a temperature interval in the heating method. The factor f' is an average value of the ratio of the t.r.m. and a.r.m. intensities acquired in the same field. Ideally it should be determined experimentally for each rock, but this is not always possible; it must be greater than unity and is unlikely to be greater than 2 in lunar samples (Stephenson *et al.* 1975). Figure 2 shows an a.r.m. palaeointensity determination for sample 62235.

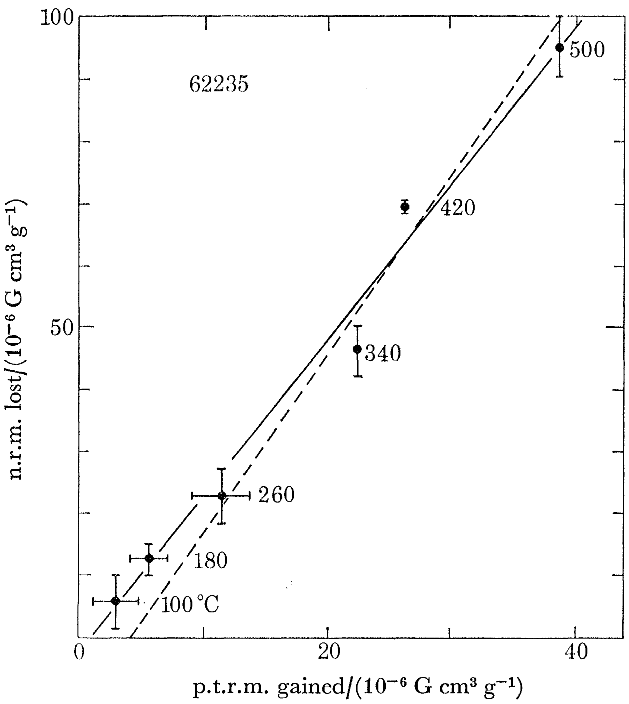

FIGURE 1

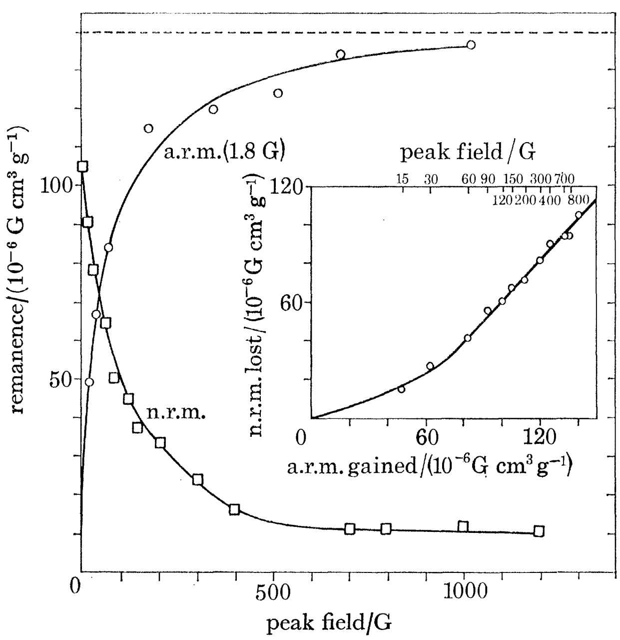

FIGURE 2

FIGURE 1. Palaeointensity determination on sample 62235, using the heating method: the dotted line shows expected larger intercept on p.t.r.m. axis (Stephenson *et al.* 1975). The two slopes give H_a = 1.2 G and 1.4 G respectively.

FIGURE 2. Palaeointensity determination on sample 62235 using the a.r.m. method (H_a = 1.4 G). The initial curved part of the line in the inset graph shows the presence of secondary magnetization in the rock.

In figure 3 palaeointensity determinations by the present authors and other workers are plotted against rock ages. With one exception (15498, Gose *et al.* 1973) the results are from crystalline rocks. Sample availability does not generally allow both the heating and a.r.m. methods to be used on each rock; in the two samples where this has been done, the agreement is very good in one (62235, Stephenson & Collinson 1974) and reasonable in the other (70215, Stephenson *et al.* 1974).

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The uncertainty of the determinations is somewhat greater than would normally be acceptable, and the errors are difficult to assess. In the authors' a.r.m. method the error chiefly arises from the uncertainty in f', to which a maximum error of ± 33 % has been attached (Stephenson *et al.* 1975), and thus also to the intensity values. Sample 68416 (Stephenson & Collinson 1974) has had a complex history, with probably two heating events, and the a.r.m. data are subject to some additional error: an error of a factor of 2 has been assigned to this intensity. In the absence of any stated errors in results obtained by other workers it is not always possible to estimate such errors, and a nominal factor of 2 has been assigned to these intensities. There is uncertainty in intensities from 10022 and 12022 (Helsley 1970, 1971) because of the somewhat incomplete heating method used, and from 15058, 15495 and 15535 (Banerjee & Mellema 1974): these authors based their technique on single-domain theory, whereas much of the n.r.m. in lunar rocks is carried by multidomain iron (Stephenson & Collinson 1974).

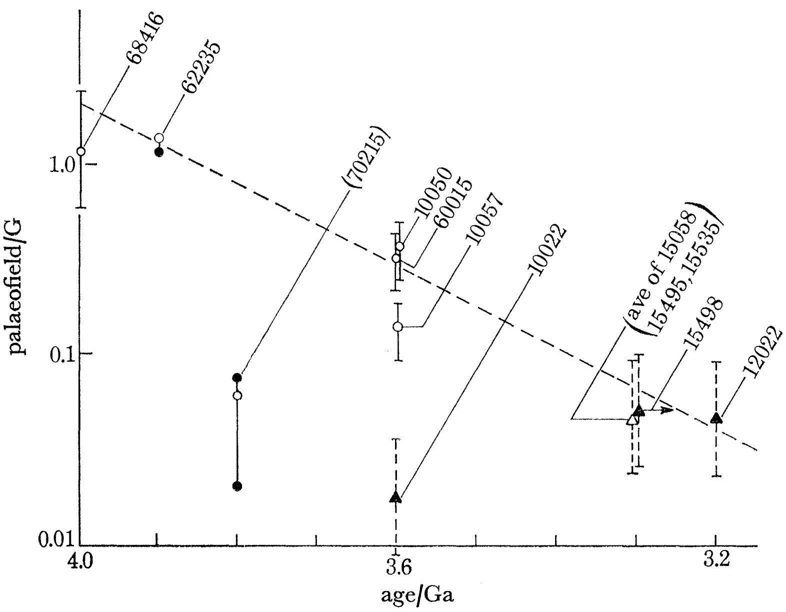

FIGURE 3. Lunar magnetic field palaeointensities plotted against the age of the samples. Open and full symbols show results from a.r.m. and heating method respectively: circles show determinations by present authors and triangles by other workers, with estimated errors. The value for 15498 has been recalculated from Gose *et al.*'s (1973) data.

When the variation of field intensity with time is investigated, difficulties arise through interpretation of ages quoted in the literature. Some are crystallization ages which correspond also to the age of the t.r.m. in the rock, whereas in others such a straightforward interpretation does not appear possible. At the time of writing the authors believe that the ages shown are reasonable, but errors are not given because of the difficulty of assessing them.

DISCUSSION

It is tentatively concluded from figure 3 that there is evidence for decay of the lunar magnetic field over the time interval represented by the rocks. The trend depends rather heavily on the two oldest samples 68416 and 62235. However, while the result from 68416 is somewhat uncertain in view of the complex result obtained, the intensity obtained from 62235 is probably the most satisfactory in that there is good agreement from the two independent methods used.

If the lunar field about 4000 Ma ago had an intensity near 1 G (10^{-4} T), there are implications for the origin of the field. For an equatorial surface field of 1.3 G (62235) the Runcorn–Urey theory would require the Moon to be uniformly magnetized to an intensity of 0.31 G (310 A/m). Pearce *et al.* (1973) show that lunar basalts typically have a saturated remanence of about 3×10^{-3} G (3 A/m); the average free iron content is about 0.1 % by mass and therefore, if such iron content and properties are typical of the whole Moon, magnetically saturated free iron must be present to about 10 % by weight to provide the above surface field. For the primaeval magnetization to be acquired as an isothermal remanence an interplanetary field of the order of 500 G (50 mT) is implied early in Solar System history. This seems an improbably large field, and the iron content cannot reasonably be much increased. The alignment of single-domain iron grains in a weaker field during the 'gas sphere' phase of formation, an alternative process proposed by Runcorn & Urey (1972), seems unlikely because of the improbability of a sufficient proportion of the grains being in the very narrow stable single-domain range.

Thus, although there are difficulties associated with the existence of a molten, conducting core early in the Moon's history and its functioning as a field-generating dynamo, on present evidence it seems the most likely origin of the field. The decay of the field, tentatively inferred from figure 3, can, of course, be equally well explained on either theory: there is as yet insufficient evidence to distinguish between the likely times or time intervals involved in radioactive heating of the lunar interior or the cooling of the core and cessation of dynamo action. If variations of the field intensity are seen, superimposed on a general decrease, these can be accommodated only by a dynamo origin of the field (in which variations may occur), but the intensity data are not yet reliable enough to distinguish such variations and more data are required to confirm or discount a strong early field and its decrease with time.

Some uncertainty exists about the importance of shock, associated with meteorite impacts, on the magnetism of lunar rocks. Among the relevant aspects are shock-induced remanent magnetism in a lunar magnetic field, t.r.m. acquisition through shock heating and magnetic field generation in a plasma associated with the impact. Cisowski *et al.* (1974) have shown that a stable shock remanence, proportional to the ambient field, can be acquired by lunar dust through shocks of up to 30 kbar (3000 MPa), and Fuller (1974) reports that shock can harden an existing n.r.m. and, in an ambient field of 0.01–1.0 G (1–100 μT), produce a remanence comparable in intensity to that observed in lunar samples. However, the iron content of lunar dust and breccias has different magnetic properties to that in the crystalline rocks, and further investigations on the latter type are desirable, since they are the best candidates for palaeointensity determinations. The question of impact-generated magnetic fields is still unresolved (Hide 1972), but a strengthening of the trend suggested in figure 3 by further data would be strong evidence against their importance.

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