ON THE INTENSITY OF THE ANCIENT LUNAR MAGNETIC FIELD.

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There is now evidence that the lunar rocks possess a component of weak, stable magnetization of thermo-remanent origin. In many samples, from all the Apollo sites, this weak NRM persists in demagnetizing alternating fields greater than 250 Oe; in those fewer samples where thermal demagnetization has been carried out, the NRM persists up to the Curie point of iron ($\sim 780^{o}C$) (1)(2)(3). A soft component is observed in many samples but this is usually removed in an alternating field of about 30 Oe and was probably acquired in the spacecraft (4). Such an IRM acquired in some strong field which could hardly exceed a few gauss could not persist against a high demagnetizing alternating field. Had an IRM been acquired while the sample was on the Moon, radiation hardening proposed by Butler & Cox (5) might increase the coercivity of the sample but does not seem to provide the order of magnitude change required by the observations. Thus a magnetizing field of the order of 250 Oe is required and this seems an unlikely event in lunar history.

The acquisition of viscous magnetization by the samples is very variable, many of the crystalline rocks showing no detectable acquisition on a laboratory time-scale in fields of the order of 1 Oe. In other samples, extrapolation of the VRM magnitude acquired in the laboratory to lunar time intervals showed that the observed NRM could not be explained by this process (6). Subsequent decay of a VRM acquired early in the Moon's history would also be expected in the near-zero field which has apparently existed on the Moon in its later history.

The effects of shock in producing or modifying remanent magnetism in lunar samples are not yet fully understood, nor is the possibility of magnetization by transient fields accompanying meteorite impacts. However, the available data is consistent with the hypothesis that the stable component of NRM found in the rocks, and in particular the crystalline samples, is a thermoremanent magnetization acquired in a lunar magnetic field at the last cooling from high temperature.

The limited number of determinations of this ancient field intensity by the Thellier-Thellier and ARM methods has been interpreted as possibly showing a decrease with time (7) from about 1.0 Oe at 4.0 by to 7000 γ at 3.2 by ago but Cisowski et al (8) have recently estimated lunar field palaeointensities using simply the ratio of NRM remaining after demagnetization in 100 Oe peak field (NRM_{100}) to the saturated IRM (IRM_s). This measure of the ancient field intensity is bound to be subject to error, because, as the samples vary in coercivity, grains with coercivities of less than 100 Oe will contribute to IRM_s but any NRM which they carry (and there is evidence that coercivities in excess of only 30 Oe can carry NRM (9) will not contribute to NRM_{100}. Since the distribution of coercivities is invariably weighted towards the lower values (see ARM curves of Stephenson et al (9) for examples) then variations in the coercivity distribution will lead to marked variations in palaeofield estimates using this method). Moreover some samples which are unsuitable for palaeointensity determinations such as those

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containing iron grains which are magnetically unstable over geological times will depress the NRM_{100}/IRM_s ratio and give underestimates of the field since the unstable grains will contribute to the saturated IRM on a laboratory time scale.

Cisowski et al have checked their method against conventional results obtained on samples 15498 and 62235 and obtain estimates which agree in the former case and are different by a factor of 5 in the latter. If a factor of 5 is taken to be the standard deviation of a single estimate, their results are not inconsistent with the simple field decay suggested by Stephenson et al (7), since a line of slope equal to that of Stephenson et al drawn on their diagram (fig. 1), and with limits corresponding to a factor of ± 5, includes about 7 of the 13 non-breccia samples (about 9 out of the 13 points should lie within the limits if the factor 5 were the standard deviation). Indeed if the mare basalts alone are considered the relevant fraction is 14 out of 16 using the un-normalised NRM_{100} and this tends to confirm the trend. It thus seems that the method of Cisowski et al is tantalisingly just too approximate in the case of the non-mare basalts (perhaps due to greater variations in magnetic properties between samples) to reinforce the trend suggested by Stephenson et al. While the results of Dunlop et al (10) on single domain and pseudo-single domain magnetite show differences in behaviour between TRM and ARM, results on samples containing multidomain iron grains (11) did not show evidence of any discrepancies.

Runcorn (12) has shown that the fact that the present dipole moment of the Moon is negligible provides strong support to the hypothesis that the magnetizing field was of internal origin. The existence of an iron core in which a dynamo process could have occurred is still not proved. However Runcorn (13)(14) inferred the existence of a core of radius 0.1 - 0.3 of the Moon from a convection theory of its non-hydrostatic figure. Recently various lines of evidence support this conclusion: (1) a meteorite impact on the far side of the Moon gives a reduced seismic wave velocity near its centre consistent with a core not greater in radius than 400 km. (2) the best value of the moment of inertia factor 0.392 is consistent with an iron core of this radius.
(3) electromagnetic induction characteristics on the Moon's entry into the magnetotail seems to require a highly conducting core.

The high palaeointensity (1.3 G) found at 3.9 - 4.0 AE is at first sight surprising in so small a core and it virtually excludes the alternative explanation in terms of a primeval permanent magnetization of a cold accreted Moon put forward by Runcorn & Urey (15). The field at the surface of the core would be about 80-100 G. However that the radius of the core is small, compared to that of the Earth, Venus or Mercury does not mean that the intensity must be small. The field intensity produced by a dynamo process is a complex and unknown function of the heat source concentration, the thermodynamic efficiency of thermal convection viewed as a heat engine and the Moon's rotation rate. The Joule heat generated by the electric current necessary to sustain the field is negligible. It is the disappearance of the field since 3.2 by ago which is to be plausibly attributed to the small core radius, on which the magnetic Reynolds number depends. When this non-dimensional number became sub-critical dynamo action ceased (Runcorn et al (16).

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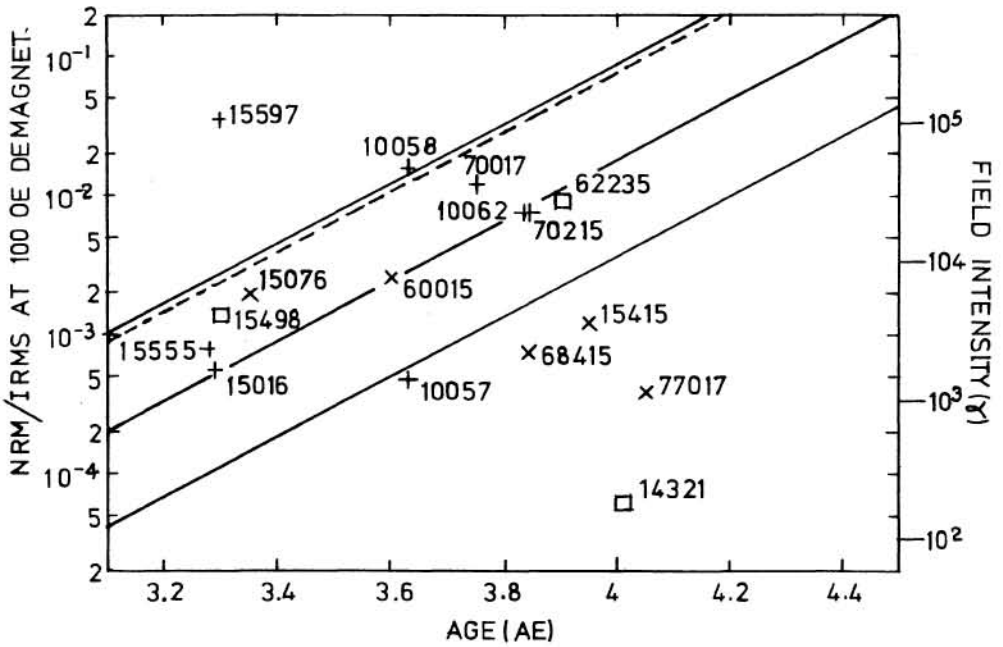

Fig. 1. Diagram of Cisowski et al (8) on which is superimposed a line of slope equal to that of Stephenson et al (7) with limits corresponding to a factor of ± 5. Dashed line shows suggested palaeo-intensity-time plot of Stephenson et al (7). Mare basalts (+), Highland crystalline rocks (×), breccias (□).