The Intensity of the Ancient Lunar Field From Magnetic Studies on Lunar Samples

A. Stephenson, D. W. Collinson, and S. K. Runcorn
Department of Geophysics and Planetary Physics
School of Physics,
The University, Newcastle-upon-Tyne, England

Palaeointensity determinations on Apollo 11, 16, and 17 rocks have indicated that from 3.9 to 4.0 AE ago the strength of the surface lunar magnetic field was about 1.3 Oe, while there is evidence from younger rocks that a field of about one quarter of this value was present at a later time (3.6 AE).

One of the objectives of magnetic studies on lunar samples is the determination of the intensity of the ancient lunar field present when the rocks were formed. Rocks containing hard components of magnetization have been found by many investigators, suggesting that this is a primary magnetization acquired at the time of formation; but estimates of the strength of the field which was present have been relatively few in number (refs. 1–4).

The usual method for estimating palaeointensities is by using the Thellier method, which involves a comparison of the natural remanent magnetization (NRM) lost by thermal demagnetization and the partial thermoremanent magnetization (PTRM) gained in a known field in the same temperature interval. A further method which can be used to estimate palaeointensities is one using anhysteretic remanent magnetization (ARM). The way in which this has been used here is similar to the Thellier method except that field replaces temperature. Thus the NRM lost by alternating field (AF) demagnetization is compared with the ARM gained in a known direct field for various values of peak alternating field. Provided that the coercivity spectrum of ARM is the same as TRM (and that the NRM is a TRM) and if the ratio f′ of the relative strengths of TRM to ARM acquired in the same direct field is known, the ancient lunar field can be estimated.

To enable the same tumbling system to be used for alternating field demagnetization and for building up ARM, a perspex holder was used to provide the unidirectional field. The holder contained a fixed magnet system into which the sample fitted. This was then placed in the tumbling system within the demagnetizing coil, the coercivity of the magnets being high enough to be unaffected by the maximum peak demagnetizing field (1360 Oe). The unidirectional field was originally 4 Oe, but was later reduced to 1.8 Oe to reduce nonlinearities between ARM and direct field. A fuller description of the method is given in another paper (Ref. 5) together with the determination of the factor f′ from TRM measurements on a synthetic multidomain iron sample and Apollo 11 basalt sample 10050,33. These gave values for f′ of 1.28 and 1.40, respectively, an average value of 1.34 being used in the palaeointensity determinations.

The factor f′ may theoretically have any value greater than unity and thus it is possible that values significantly different from 1.3 may occur in some samples. However, provided that a significant fraction of the NRM is carried by grains with blocking temperatures less than about 670° C (ref. 5), f′ is expected to be within a few tens of percent of the above value. A direct determination of f′ from the thermal demagnetization curve of the NRM of 62235 yielded a value of about 1.3 in agreement with the expected value.

Results

Figure 1 shows the result of a determination on 62235,53 by the Thellier method in an applied field of 0.5 Oe. The necessary heating was carried out in a continuously pumped enclosure to minimize the effects of oxidation, and from the slope of the graph the ancient field intensity is 1.2 Oe (ref. 3). Using the ARM method (fig. 2) where the NRM lost up to a particular field value is plotted against the ARM gained in the same peak field, gives a palaeofield h_p of 1.4 Oe (i.e., $h_p = \frac{\text{slope}}{1.34} \times h_A$) where h_A is the applied direct field (in this case 1.8 Oe). The initial nonlinearity between NRM and ARM may be explained by partial demagnetization of the NRM by solar heating during the lunar day, and this is consistent with the virtually constant direction obtained (fig. 3) during the AF demagnetization of the major part of

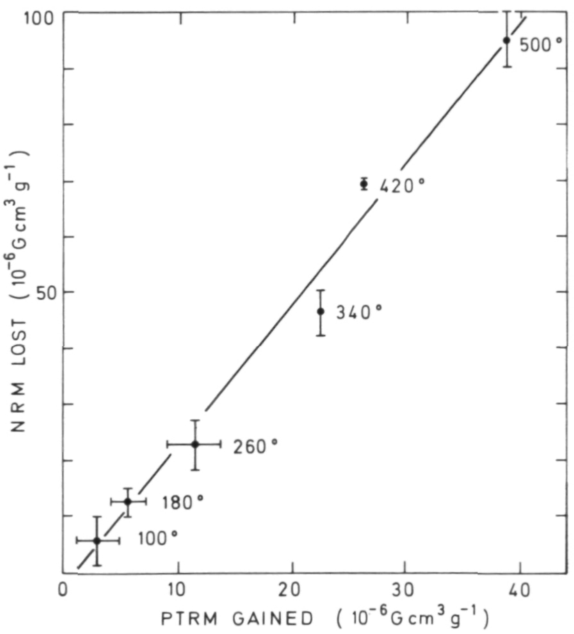

Figure 1.—*Determination of palaeointensity (1.2 Oe) on sample 62235,53 by Thellier method.*

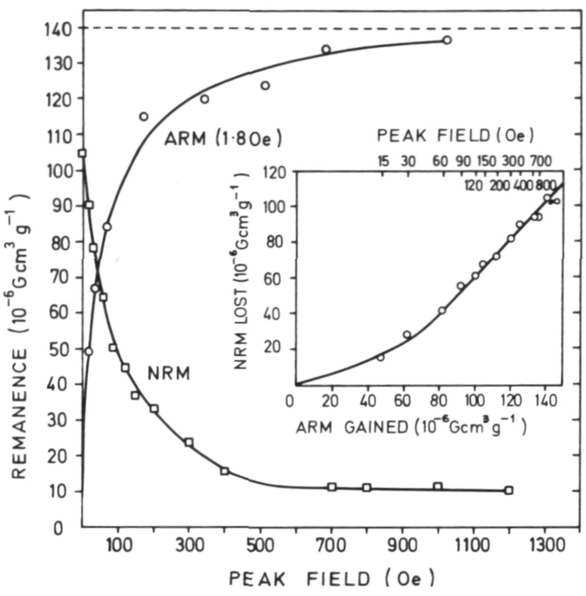

Figure 2.—*Determination of palaeointensity (1.4 Oe) on sample 62235,53 by ARM method.*

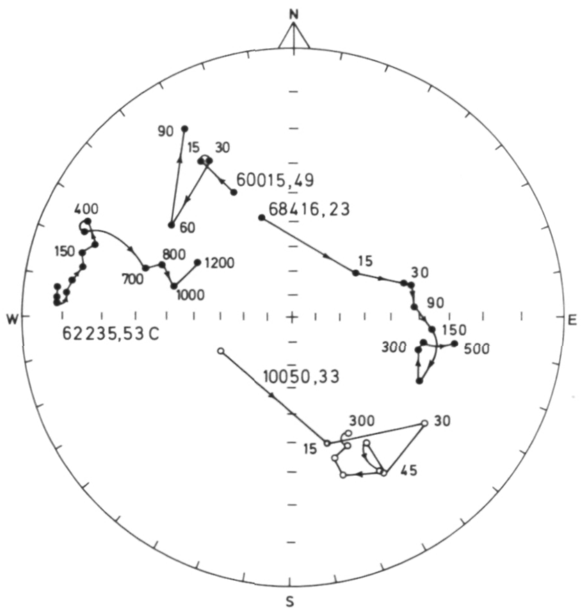

Figure 3.—*Direction changes of the NRM of samples during AF demagnetization. Peak field values are indicated.*

the remanence. These two determinations by different methods suggest very strongly that the NRM is of thermoremanent origin and was acquired in a surface field of about 1.3 Oe at 3.9 AE, this being the time at which this KREEP basalt crystallized (ref. 6).

Further evidence for a surface field of this magnitude at this time comes from a field determination using ARM on sample 68416,23, which is a gabbroic anorthosite. The result (fig. 4) clearly indicates that two components approximately opposed to one another are present in this rock, since on initial demagnetization of the NRM an increase in intensity is observed. If it is assumed that the primary component is the harder of the two, then since a straight line is obtained in the NRM–ARM plot above a peak demagnetizing field of 150 Oe, it appears that this slope (which yields a palaeointensity of about 1.2 Oe) must represent this component. This interpretation is also consistent with the observation that the direction remains constant above 150 Oe (fig. 3). Evidence that the moderately hard secondary component almost opposed to the primary may be a partial TRM acquired on subsequent heating to a temperature less than the Curie point of iron (770° C) comes from studies of the thermal history of the rock. It has been found that while the crystallization age of the rock is 4.0 AE (ref. 7), secondary reheating has taken place some 150 My after its formation (ref. 8). This suggests that at this later time a field which was comparable to 1.2 Oe must have been present, and that either the field or the rock must then have been in almost reverse orientation. The palaeointensity of 1.2 Oe determined from the primary component (4.0 AE) is very similar to the 1.3 Oe average field determined from 62235,53 above (3.9 AE).

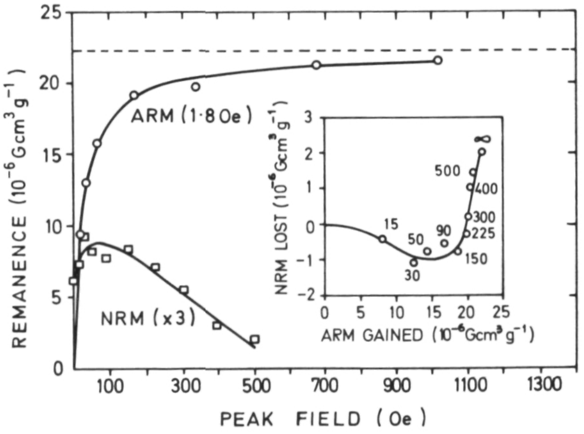

Figure 4.—*Determination of palaeointensity (1.2 Oe) on primary component of sample 68416,23 by ARM method.*

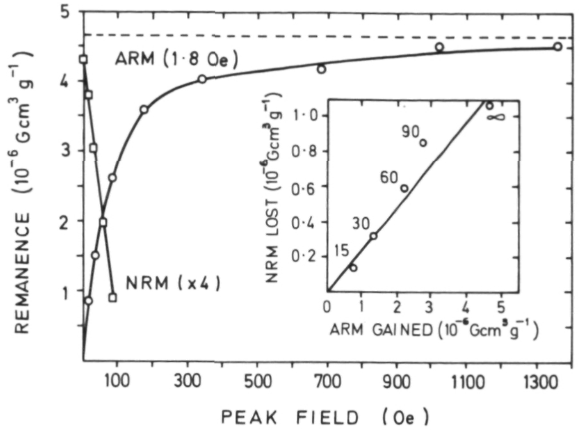

Figure 5.—*Determination of palaeointensity (0.33 Oe) on sample 60015,49 by ARM method.*

A determination using ARM on an anorthosite sample 60015 yielded a paleointensity of 0.33 Oe. Although this was based only on an initial demagnetizing curve up to 90 Oe peak field (fig. 5), there was no change in direction during this procedure and the extrapolated total loss of magnetization at infinite field also lay on the slope of the NRM-lost-ARM-gained plot. This means that the NRM is indistinguishable from TRM. The age of this sample is 3.58 AE (ref. 9).

A determination on an Apollo 11 basalt sample 10050,33 yielded a field of 0.38 Oe after removal of a large secondary component (fig. 6). Direction changes on demagnetization also support this interpretation. This sample is probably of similar age to 10057, which is a basalt of age 3.63 AE (ref. 10) and which gave a tentative field value of 0.14 Oe.

Other samples which for various reasons did not yield satisfactory results (ref. 11)

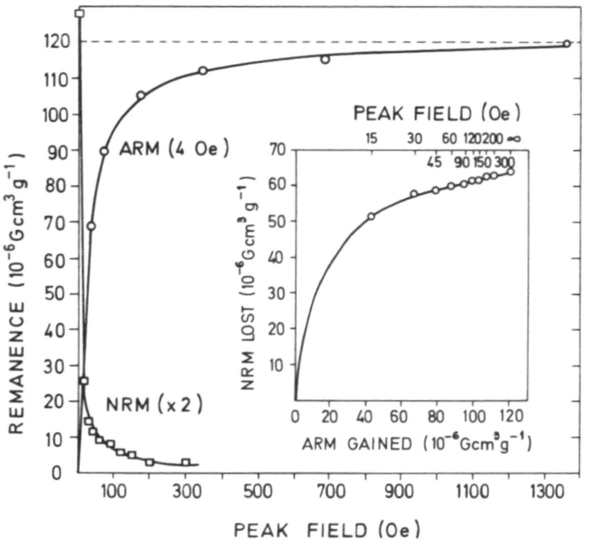

Figure 6.—*Determination of palaeointensity (0.38 Oe) on sample 10050,33 after removal of large secondary component.*

were 76315 and 77035. Another two samples which gave results of doubtful validity were 70215 and 70017. Although little confidence could be placed in the results, the samples gave very similar palaeointensity values by two different methods. Sample 70017,78 gave 0.5 ± 0.2 Oe by the Thellier method, and 0.3 Oe with the use of ARM. Sample 70215,45 gave a field of 0.04 Oe to within a factor of 2 by the Thellier method compared with 0.06 Oe with the use of ARM.

Conclusion

There is strong evidence from these results that some 4.0 AE ago the surface field was as high as 1.3 Oe and that at 3.6 AE it was somewhat less than this. Whether this apparent decrease occurred gradually or whether it was part of more random variations is a question which at present cannot be answered. The presence of a strong field does, however, have important implications regarding lunar history.

If a convecting lunar core was responsible for the field, then in terms of the magnetic moment per unit volume of core, the lunar core would have to be much more efficient than that of the Earth, assuming that a lunar core cannot exceed about one-fifth of the lunar radius. Permanent magnetization of the Moon acquired in some way during the formation process could not lead to such a high surface field unless the concentration of iron increases considerably toward the center, since to produce 1.3 Oe at the surface, the average magnetization of the Moon would exceed the saturation remanent magnetization of typical lunar basalts.

It is clear that further plaeointensity studies on lunar samples are necessary to evaluate the behavior of the ancient lunar field with time.

References

1. HELSLEY, C. E., Magnetic Properties of Lunar 10022, 10069, 10084 and 10085 Samples. *Proc. Apollo 11 Lunar Sci. Conference, Geochimica et Cosmochimica Acta,* Supplement 1, Vol. 3, 1970, pp. 2213–2219.
2. GOSE, W. A., D. W. STRANGWAY, AND G. W. PEARCE, A Determination of the Intensity of the Ancient Lunar Magnetic Field. *The Moon,* Vol. 7, 1973, pp. 198–201.
3. COLLINSON, D. W., A. STEPHENSON, AND S. K. RUNCORN, Magnetic Properties of Apollo 15 and 16 Rocks. *Proc. Fourth Lunar Science Conference, Geochimica et Cosmochimica Acta,* Supplement 4, Vol. 3, 1973, pp. 2963–2976.
4. FULLER, M., Lunar Magnetism. *Rev. Geophysics & Space Physics,* Vol. 12, 1974, pp. 23–70.
5. STEPHENSON, A., AND D. W. COLLINSON, Lunar Magnetic Field Palaeointensities Determined by an Anhysteretic Remanent Magnetization Method. *Earth Planet. Sci. Letters,* in press, 1974.
6. NYQUIST, L. E., N. J. HUBBARD, P. W. GAST, B. M. BANSAL, H. WIESMANN, AND B. JAHN, Rb-Sr Systematics for Chemically Defined Apollo 15 and 16 Materials. *Proc. Fourth Lunar Science Conference, Geochimica et Cosmochimica Acta,* Supplement 4, Vol. 2, 1973, pp. 1823–1846.
7. KIRSTEN, T., P. HORN, AND J. KIKO, ^{39}Ar-^{40}Ar Dating and Rare Gas Analysis of Apollo 16 Rocks and Soils. *Proc. Fourth Lunar Sci. Conference, Geochimica et Cosmochimica Acta,* Supplement 4, Vol. 2, 1973, pp. 1757–1784.
8. HUNEKE, J. C., E. K. JESSBERGER, F. A. PODESEK, AND G. J. WASSERBURG, ^{40}Ar/^{39}Ar Measurements in Apollo 16 and 17 Samples and the Chronology of Metamorphic and Volcanic Ac-

tivity in the Taurus-Littrow Region. *Proc. Fourth Lunar Science Conference, Geochimica et Cosmochimica Acta,* Supplement 4, Vol. 2, 1973, pp. 1725–1756.

9. TATSUMOTO, M., P. D. NUNES, AND R. J. KNIGHT, U-Th-Pb Systematics of Some Apollo 16 Samples. In *Lunar Science IV,* J. W. Chamberlain and C. Watkins, eds., Lunar Science Institute, Houston, 1973, pp. 705–707.
10. PAPANASTASSIOU, D. A., G. J. WASSERBURG, AND D. S. BURNETT, Rb-Sr Ages of Lunar Rocks From the Sea of Tranquility. *Earth Planet. Sci. Letters,* Vol. 8, 1970, pp. 1–19.
11. STEPHENSON, A., D. W. COLLINSON, AND S. K. RUNCORN, Lunar Magnetic Field Palaeointensity Determinations on Apollo 11, 16 and 17 Rocks. *Proc. Fifth Lunar Science Conference, Geochimica et Cosmochimica Acta,* in press, 1974.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1977 O—592–572