NATURAL REMANENT MAGNETIZATION OF ANTARCTIC METEORITES

Takesi NAGATA

National Institute of Polar Research, Kaga 1-chome, Itabashi-ku, Tokyo 173

***Abstract*:** The stability of natural remanent magnetization (NRM) of various chemical groups of meteorites, which have been carefully recovered from the Antarctic ice sheet surface, is examined against the AF-demagnetization. The meteorites examined are 1 E-chondrite, 3 H-chondrites, 5 L-chondrites, 2 LL-chondrites, 3 C-chondrites, 4 achondrites, 3 irons and 1 pallasite. In general, the AF-demagnetization stability of NRM's of C-chondrites and achondrites is sufficiently high to be attributed to the natural remanence acquired in the extraterrestrial space.

NRM of 3 irons also is reasonably stable, but the NRM is very likely to be attributable to TRM acquired in the geomagnetic field on entry into the earth's atmosphere.

NRM's of E-, H-, L- and LL-chondrites and pallasite are much less stable compared with those of C-chondrites and achondrites. It cannot be recommended, therefore, to use those meteorites having poor stability of NRM for the paleointensity research purpose.

1. Introduction

Characteristics of the natural remanent magnetization (NRM) of meteorites have already been systematically examined in fair detail by several investigators (*e.g.* STACEY *et al.*, 1961; WEAVING, 1962; BANERJEE and HARGRAVES, 1972; BUTLER, 1972; GUS'KOVA, 1972; LARSON *et al.*, 1973; BRECHER and RANGANAYAKI, 1975; NAGATA and SUGIURA, 1976). The main interest in the meteoritic NRM study is concerned with the paleomagnetic field of possible meteorite parent planets or the primordial field in the interplanetary space. For such a research purpose, a sufficiently high stability of NRM against possible natural and artificial disturbances upon the examined meteorites is strongly required on one hand, and no or the least contamination on the meteorite samples during the period from their fall on the earth's surface to their magnetic examination also is to be seriously requested on the other hand.

The stability of NRM of meteorites against the AF-demagnetization and the thermal demagnetization has already been examined for various kinds of meteorite. Examining more than 30 stony meteorites, GUS'KOVA (1972) demonstrated that the AF-demagnetization stability of NRM of stony meteorites can be divided into two components; *i.e.* soft and hard remanent magnetizations. The soft remanence can be almost completely demagnetized by an alternating field of $\tilde{H}=10$–20 Oe, whereas the hard remanence remains in $\tilde{H}=300$–350 Oe. She pointed out further that stony meteorites could be classified into two groups, *i.e.* a group containing the hard component from 6 to 25% and the other group containing the hard component from 50 to 80%.

LARSON *et al.* (1973) examined the AF-demagnetization stability of 40 meteorites, and have concluded that almost all of the carbonaceous chondrites they studied have a stable NRM with respect to both intensity and direction during alternating field demagnetization up to 400 Oe. They pointed out that most ordinary chondrites also exhibit a stable remanence after AF-demagnetization up to 400 Oe, though some ordinary chondrites contain a large amount of low stability magnetization, and that stony-iron meteorites generally have NRM intensities and directions which are unstable to AF-demagnetization.

Examining the AF-demagnetization stability of NRMs of 21 chondrites (3 E-chondrites, 5 H-chondrites, 9 L-chondrites and 4 LL-chondrites), BRECHER and RANGANAYAKI (1975) have concluded that the relative stability of NRM and the degree of directional coherence under progressive AF-demagnetization increase in the order of sequence E→H→L→LL chondrites. BANERJEE and HARGRAVES (1972) have experimentally demonstrated, on the other hand, that three carbonaceous chondrites they examined have NRMs which are reasonably stable against the AF-demagnetization. The extremely high stability of NRM of Allende carbonaceous chondrite has been confirmed not only by these workers but also by BUTLER (1972) and SUGIURA (1977). NAGATA *et al.* (1975) also have pointed out that a carbonaceous chondrite and an achondrite have much stabler NRM than E- and H-chondrites.

Summarizing all these data of NRM stability of stony meteorites, we may conclude that NRM of stony meteorites comprises a hard remanence and a soft remanence which could be attributed to IRM and/or VRM, and that NRM of the carbonaceous chondrites generally has an extremely higher stability against AF-demagnetization than any other chondrites.

As far as NRM characteristics of meteorites are concerned, however, very little is known about how individual meteorites have been handled, particularly with respect to magnetic fields affecting the samples during the period from their fall on the earth to the laboratory magnetic study, except for very special fall-meteorites which have been carefully collected and handled throughout the period by experienced scientists.

The Yamato meteorites and the other Antarctic meteorites had fallen on the ice sheet surface in the Antarctic interior and had remained in and on the dry and cold ice sheet until the time when they were found. In collecting Yamato and other

Antarctic meteorites, each of them is put into a double shield bag by experienced scientists *in situ* without touching by naked hands. Shielded bags containing meteorite samples have been carefully transported in wooden cases from the location of meteorite finding to the sample curator's office with utmost care not to give them any magnetic field larger than 1 Oersted and not to heat them over 40°C. The recovered Antarctic meteorites can therefore be considered as the least contaminated meteorites which are ideal at present for examining their NRM characteristics.

This note will deal with the stability of NRM against AF-demagnetization test for 22 Antarctic meteorites thus recovered. The samples examined comprise 1 E-chondrite, 3 H-chondrites, 5 L-chondrites, 2 LL-chondrites, 3 C-chondrites, 4 achondrites, 3 irons and 1 pallasite.

2. Experimental Procedures

(1) The meteorite samples examined were kept in a practically non-magnetic space ($<10^{-3}$ Oe) within a high-μ metal case in order to diminish VRM acquired in the geomagnetic field, until fluctuations of intensity and direction of NRM become less than 1% and 3° respectively.

(2) The AF-demagnetization of NRM of each sample is successively carried out from 0 to 200–400 Oe peak in alternating field in a practically zero DC-field, and the residual magnetization is measured by a PAR spinner magnetometer.

(3) IRM acquisition process is examined for each meteorite, and the IRM coefficient defined by $b \equiv (\mathrm{IRM})/\mathrm{H}_{\mathrm{ex}}^2$ is determined for the purpose of evaluating an applied DC-magnetic field (H_{ex}) to produce IRM equivalent to NRM. The stability of IRM thus acquired against AF-demagnetization also is measured.

(4) A magnetic hysteresis curve of each sample at room temperature in -16 to $+16$ kOe is measured, the magnetic parameters such as saturation magnetization (I_s), saturation remanent magnetization (I_R), coercive force (H_c) and remanence coercive force (H_{Rc}) being determined.

(5) An approximate degree of VRM acquisition is determined by measuring a time-decay in non-magnetic space of IRM acquired in several different values of H_{ex}.

(6) Thermomagnetic curves of each meteorite are measured in 10^{-5} torr atmosphere in order to estimate the ferromagnetic component which contributes to NRM.

3. Stable NRM

As already pointed out, carbonaceous chondrites generally have a much stabler NRM compared with the other chondrites. It may be observed in the present study that achondrites also have NRM as stable as that of carbonaceous chondrites.

3.1. Carbonaceous chondrites

NRM's of all 3 examined carbonaceous chondrites (Yamato-693 (c)-1, Yamato-693 (c)-3 and Yamato-74662) are stable with respect to intensity and direction, as illustrated in Figs. 1a and 1b. In Fig. 1b, changes in the direction of residual magnetization after AF-demagnetization up to 50, 100, 150 and 200 Oe peak respectively are illustrated together with the initial direction of NRM. It seems that NRM of Yamato-74662 carbonaceous chondrite is very stable.

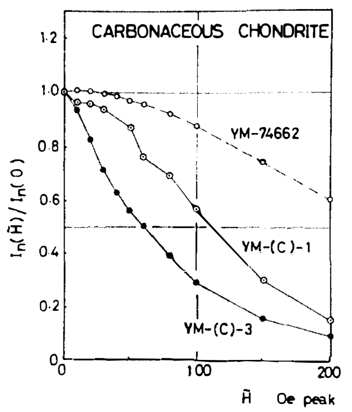


Fig. 1a. AF-demagnetization curves of NRM intensity for carbonaceous chondrites.

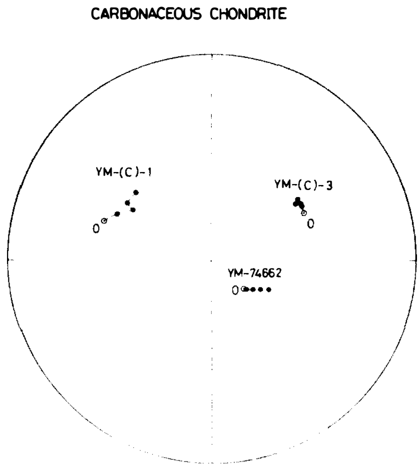


Fig. 1b. AF-demagnetization curve of NRM direction for carbonaceous chondrites.

To numerically represent the AF-demagnetization stability of NRM with respect to both the intensity and direction for an inter-comparison purpose among various meteorites, the ratio of residual magnetization after AF-demagnetizing to 100 and 200 Oe to the original NRM, *i.e.* $I_n(100)/I_n(0)$ and $I_n(200)/I_n(0)$ respectively, and the deviation in angle of the direction of residual magnetization after AF-demagnetizing to 100 and 200 Oe, *i.e.* Δ_{100} and Δ_{200} respectively, are summarized in Table 1, where the original NRM intensity, ($I_n(0)$), saturation gnetizationma (I_s), saturation remanent magnetization (I_R) and coercive force (H_c) measured at room temperature also are given.

The high stability of NRM of the three carbonaceous chondrites could be attributed to their high coercive force ($H_c \sim 150$ Oe). As reported by BANERJEE and HARGRAVES (1972), LARSON *et al.* (1973) and SUGIURA (1977), Allende carbonaceous chondrite also has an extremely stable NRM against AF-demagnetization

Table 1. Stability of NRM of meteorites against AF-demagnetization.

Sample	$I_n(0)$ ($\times 10^{-6}$ emu/gm)	$\frac{I_n(100)}{I_n(0)}$	$\frac{I_n(200)}{I_n(0)}$	Δ_{100} (Degree)	Δ_{200} (Degree)	I_s (emu/gm)	I_R (emu/gm)	H_c (Oe)
(E-chondrite)								
Yamato-691(a)	3,355	0.026	0.012	31	151	48.0	0.035	12
(H-chondrite)								
Yamato-694(d)	567	0.026	0.012	156	172	32.3	0.60	23
Yamato-7301(j)	902	0.15	0.16	167	137	15.5	0.14	16
Yamato-74647	2,176	0.030	0.064	38	123	27.9	0.34	14
(L-chondrite)								
Yamato-7305(k)	106	0.13	0.096	85	168	14.3	0.045	8
Yamato-7304(m)	621	0.062	0.058	16	55	16.6	0.003	4
Yamato-74191	211	0.047	0.041	141	133	6.8	0.22	30
Yamato-74362	302	0.093	0.065	149	120	8.1	0.27	38
Allan Hills 769(i)	1,993	0.017	0.009	10	39	8.4	0.52	160
(LL-chondrite)								
Yamato-74442	49	0.30	0.17	44	56	6.1	0.22	85
Yamato-74646	614	0.039	0.013	9	146	3.2	0.026	20
(C-chondrite)								
Yamato-693(c)-1	1,005	0.29	0.095	14	19	10.2	1.60	152
Yamato-693(c)-3	3,764	0.56	0.15	4	5	11.1	1.76	175
Yamato-74662	41,610	0.88	0.60	4	11	0.81	0.102	149
(Achondrite)								
Yamato-692(b)	15.4	1.53	0.81	15	24	0.19	0.0035	42
Yamato-7308(l)	11.5	0.42	0.31	5	23	0.53	0.0027	13
Yamato-74013	2.5	0.69	0.29	6	20	0.17	0.0012	10
Yamato-74159	22.7	1.02	0.72	6	7	0.07	0.0002	40
(Iron)								
Yamato-75031	1,188	0.82	0.32	8	3			
Yamato-75105	64,430	0.23	0.040	5	19	225	0.025	5
Allan Hills 762(b)	18,430	0.18	0.062	11	24	210	0.30	60
(Pallasite)								
Yamato-74044	2,758	0.046	0.040	95	135			

and it has a high coercive force ($H_c = 143$ Oe). A special remark may have to be made on an unusually high value of NRM of Yamato-74662, which amounts to 4.16×10^{-2} emu/gm and $I_n(0)/I_s = 5.1 \times 10^{-2}$.

3.2. *Achondrites*

NRM's of all four examined achondrites (2 diogenites, Yamato-692(b) and Yamato-74013, and 2 howardites, Yamato-7308(1) and Yamato-74159) are as stable as those of the three carbonaceous chondrites as illustrated in Figs. 2a and 2b. Especially, NRM of Yamato-74159 is so much stable against AF-demagnetization that $I_n(400)/I_n(0) = 0.34$, $I_n(600)/I_n(0) = 0.25$, $\Delta_{400} = 7°$ and $\Delta_{600} = 6°$ are observed.

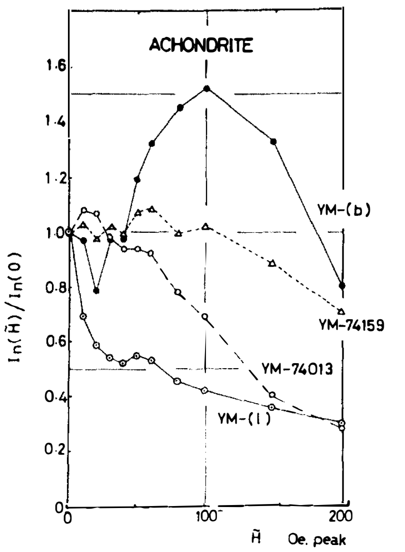


Fig. 2a. AF-demagnetization curves of NRM intensity for achondrites.

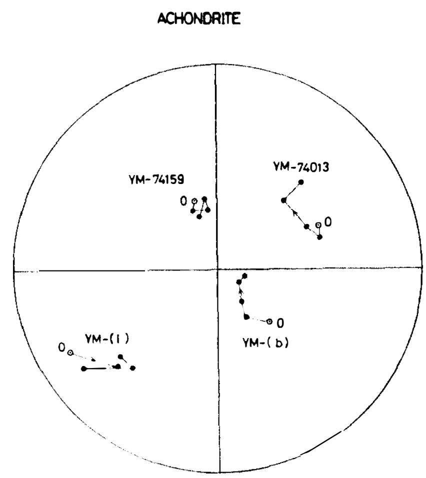


Fig. 2b. AF-demagnetization curves of NRM direction for achondrites.

No definite observation of a high stability of NRM of achondrites has yet been reported to date, but the present observed result that all the four Yamato achondrites have a stable NRM without exception may lead to a provisional conclusion that achondrites have stable NRM in general. As given in Table 1, however, their coercive force is not particularly large compared with that of H-, L- and LL-chondrites. It would then be considered that the ferromagnetic components in achondrites may comprise a magnetically hard component which is responsible for the stable NRM and a soft one which contributes to reducing the apparent value of H_c.

Since the achondrites have been believed to be the outer silicate layer component enveloping the inner metallic core in a meteorite parent planet, the stable NRM of achondrites could be interpreted to be TRM or a similar remanent magnetization of the achondrite layer acquired in the presence of a magnetic field caused in the fluidal metallic core. A special significance could therefore be put on the stable NRM of achondrites.

3.3. Irons

As shown in Figs. 3a and 3b, examined three iron meteorites (Yamato-75031, Yamato-75105 and Allan Hills 762(b)) also have reasonably stable NRM. As Yamato-75105 shows clear evidence of reheating throughout the entire body

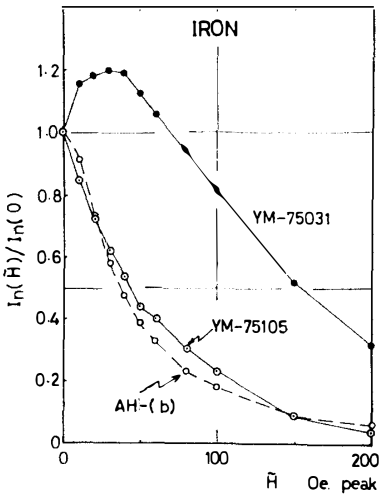


Fig. 3a. AF-demagnetization curves of NRM intensity for iron meteorites.

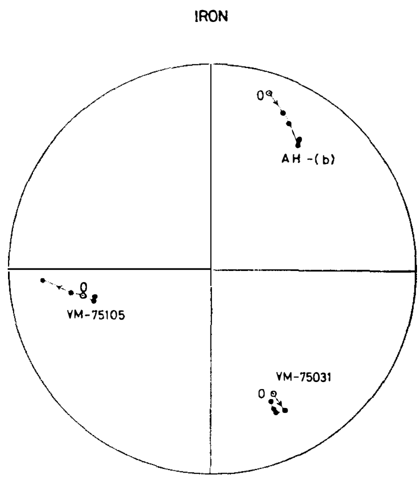


Fig. 3b. AF-demagnetization curves of NRM direction for iron meteorites.

(17.6 gm in total weight), the relatively stable NRM of this iron meteorite could be attributed to TRM acquired on entry into the earth's atmosphere in the presence of geomagnetic field. As Yamato-75031 also is a small iron piece, weighing only 60.2 gm, it is highly probable that this iron meteorite also was reheated on entry into the earth's atmosphere to acquire TRM. Allan Hills 762(b) is not a small iron piece, weighing 1510 gm, but NRM and the magnetic properties were examined with respect to the outermost part near the fusion crust of this sample. The relatively stable NRM of this sample also could be attributed to TRM acquired in the geomagnetic field.

4. Unstable NRM

4.1. H-chondrites

NRM's of three olivine-bronzite chondrites (Yamato-694(d), Yamato-7301(j) and Yamato-74647) have been examined. As shown in Figs. 4a and 4b, all the three H-chondrites have very unstable NRM. Particularly, the stability of NRM direction against AF-demagnetization is so poor that NRM of such meteorites could not be used for the paleomagnetic study.

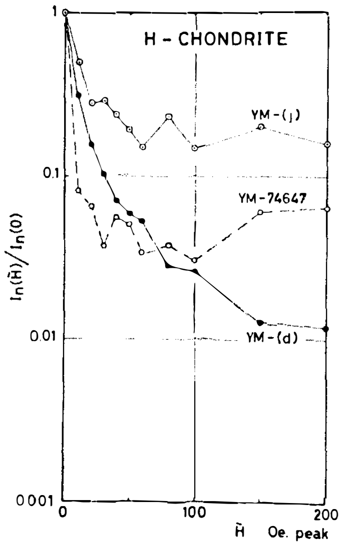


Fig. 4a. AF-demagnetization curves of NRM intensity for H-chondrites.

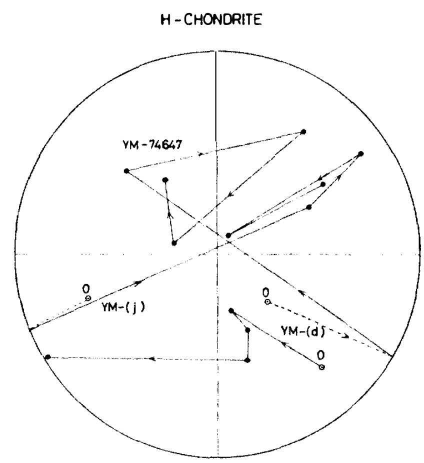


Fig. 4b. AF-demagnetization curves of NRM direction for H-chondrites. (Dotted lines are in the opposite hemisphere).

4.2. L-chondrites

As illustrated in Figs. 5a, 5b and 5c, NRM's of five olivine-hypersthene chondrites (Yamato-7305(k), Yamato-7304(m), Yamato-74191, Yamato-74362 and Allan Hills 769(i)) also are unstable against AF-demagnetization. As far as the NRM direction stability is concerned, Allan Hills 769(i) is the best among the five examined L-chondrites. This may be due to a high value of H_c of this sample.

4.3. LL-chondrites

NRM's of two LL-chondrites (Yamato-74442 and Yamato-74646) have been examined. As shown in Figs. 6a and 6b, NRM of Yamato-74646 is unstable with respect to both the intensity and direction, whereas that of Yamato-74442 is considerably stabler than the former. The higher stability of NRM of Yamato-74442 may be due to its higher value of H_c.

4.4. E-chondrite and pallasite

NRM of an enstatite chondrite (Yamato-691(a)) and a pallasite (Yamato-74044) is unstable with respect to both intensity and direction as illustrated in Figs. 7a and 7b.

As far as the relatively uncontaminated Antarctic meteorites are concerned, NRM's of E-, H-, L- and LL-chondrites and pallasite may not be considered reasonably stable against the AF-demagnetization. It seems likely that comparatively large grains of native iron in these meteorites cannot stably maintain natural remanent magnetization, if any.

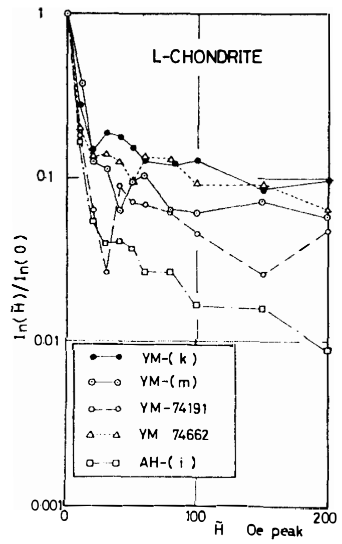
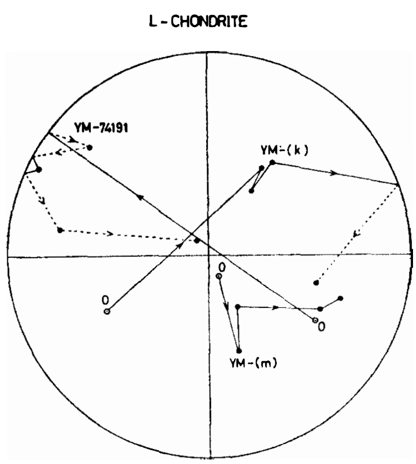


Fig. 5a. AF-demagnetization curves of NRM intensity for L-chondrites.



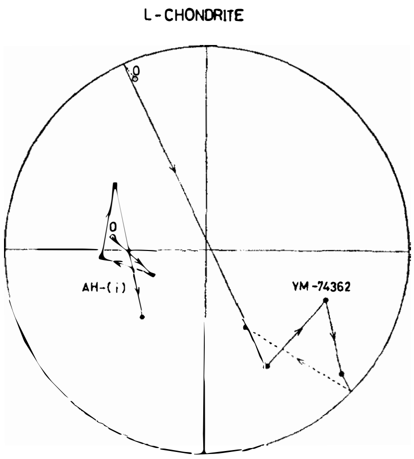


Fig. 5b. *Fig. 5c.*

Figs. 5b and 5c. AF-demagnetization curves of NRM direction for L-chondrites (Dotted lines are in the opposite hemisphere).

5. Paleomagnetism by Use of Achondrites

Although an exact physical mechanism for stable NRM of achondrite group

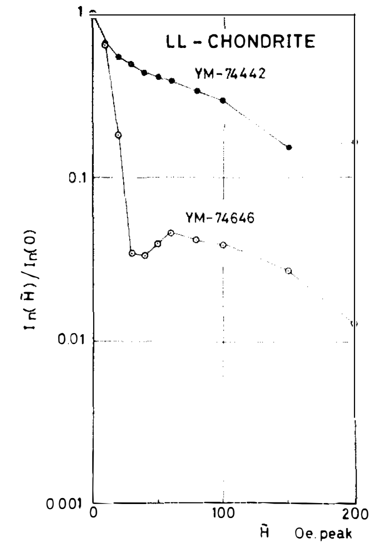


Fig. 6a. AF-demagnetization curves of NRM intensity for LL-chondrites.

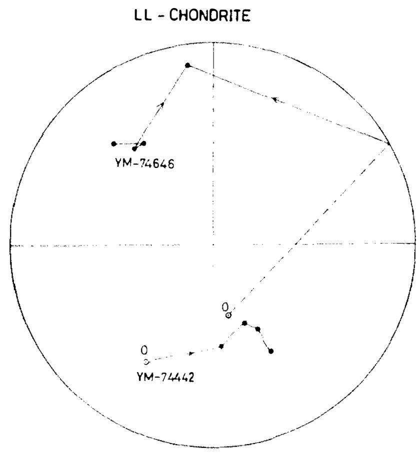


Fig. 6b. AF-demagnetization curves of NRM direction for LL-chondrites (Dotted lines are in the opposite hemisphere).

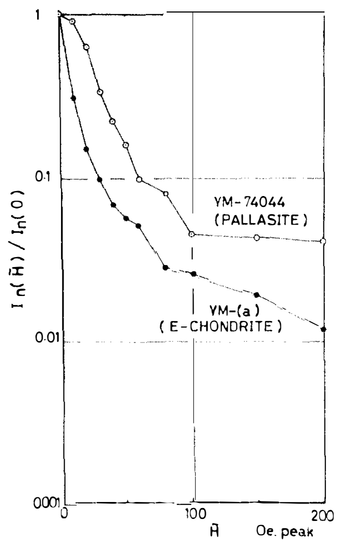


Fig. 7a. AF-demagnetization curves of NRM intensity for an E-chondrite and a pallasite.

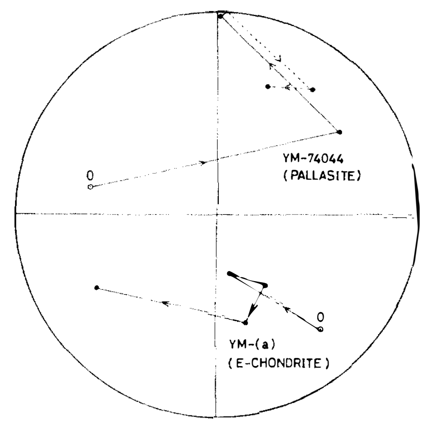


Fig. 7b. AF-demagnetization curves of NRM direction for an E-chondrite and a pallasite (Dotted lines are in the opposite hemisphere).

is not clarified in the present study, it will be highly probable that an achondrite layer which formed an outer shell of a parent planet may have acquired TRM during its cooling process in the presence of a magnetic field which might be produced by a magnetohydrodynamic dynamo within a fluidal metallic core.

Experiments of thermal demagnetization of NRM and acquisition of TRM were carried out for an achondrite sample, Yamato-7308 (l). The total TRM intensity thus acquired amounts to 3.4×10^{-4} emu/gm/Oe, where the main acquisition of *p*TRM takes place in a temperature range of 700–800°C (NAGATA *et al.*, 1976). If the cooling rate of this achondrite is fast enough to acquire the total TRM, then the paleomagnetic field intensity is estimated to be 0.034 Oe (because the NRM intensity of this achondrite is 11.5×10^{-6} emu/gm). If the cooling rate is of the order of 10°/million years, however, the acquisition of TRM can occur only below 700°K in temperature (NAGATA and SUGIURA, 1976). In such a case, a comparison of the *p*TRM acquisition curve with the thermal demagnetization curve of this sample suggests that the ambient magnetic field was about 0.13 Oe.

The paleomagnetic field for achondrite sample 74013 has been estimated with the NRM-ARM method by SUGIURA (1977) to be about 0.093 Oe. It is highly desirable that the paleointensity study will be made for a much larger number of various achondrites on the probable assumption that their NRM is due to TRM.

6. Concluding Remarks

The results of the present study on the stability of NRM against the AF-demagnetization may suggest that NRM's of carbonaceous chondrites, achondrites and iron meteorites are reasonably stable but those of E-, H-, L- and LL-chondrites are considerably less stable. As summarized in the introduction of this note, the paleomagnetic studies of various chondrites have been carried out by a number of investigators to date. NRM's of some ordinary chondrites which have been examined in these studies are reasonably stable for the AF-demagnetization as well as for the thermal demagnetization. On the assumption of TRM origin for these chondrite NRM's, the paleomagnetic field intensity for the chondrites has been evaluated to be between 0.1 to 1.0 Oe.

Among 10 samples of ordinary chondrites (*i.e.* H, L and LL) examined in the present study, NRM of a LL-chondrite, Yamato-74442, could be considered comparatively stable. Generally speaking, however, NRM's of E-, H-, L- and LL-chondrites and pallasites are considerably less stable than those of carbonaceous chondrites, achondrites and iron meteorites. It would be doubtful, therefore, to estimate the primordial magnetic field from these unstable NRM's.

Since there is a high probability that iron meteorites acquired TRM on their entry into the earth's atmosphere in the presence of geomagnetic field, because of their high thermal conductivity, comparatively stable NRM's of iron meteorites could not be safely used for the paleomagnetic study.

As already noticed, NRM's of carbonaceous chondrites are generally stable against the AF-demagnetization test. According to BANERJEE and HARGRAVES (1972), however, NRM's of three carbonaceous chondrites which they examined seem to be acquired at temperature lower than 130°C, inconsistent data being obtained on heating above 130°C. Experiments of thermal demagnetization and *p*TRM acquisition of a carbonaceous chondrite, Yamato-74662, also have shown that NRM of this sample is thermally unstable above about 100°C. The ambient magnetic field derived on the assumption that NRM of carbonaceous chondrites was acquired by the *p*TRM mechanism is about 1.1 Oe for Allende (BUTLER, 1972; BANERJEE and HARGRAVES, 1972) and about 0.9 Oe for Karoonda (SUGIURA, 1977). If this assumption is true, the ambient magnetic field should be considered the primordial interplanetary field. It would be hardly possible to assume such an intense magnetic field as the primordial field. It seems still desirable, therefore, to experimentally clarify a reasonable acquisition mechanism of the observed stable NRM of carbonaceous chondrites.

NRM's of the four achondrites examined in the present work are reasonably stable. As briefly discussed in Section 5, it would be highly probable to presume that the stable NRM of achondrites is attributable to TRM of the outer shell of a parent planet acquired during the period when the inner core of metal was still fluidal, producing a certain planetary magnetic field by a magnetohydrodynamic dynamo mechanism. It will be desirable in the future then to specifically study NRM's and their origin of various kinds of achondrite such as diogenite, howardites, eucrites, etc. in detail.

References

BANERJEE, S. K. and HARGRAVES, R. B. (1972): Natural remanent magnetizations of carbonaceous chondrites and the magnetic field in the early solar system. Earth Planet. Sci. Lett., **17**, 110–119.

BRECHER, A. and RANGANAYAKI, R. P. (1975): Paleomagnetic systematics of ordinary chondrites. Earth Planet. Sci. Lett., **25**, 57–67.

BUTLER, R. F. (1972): Natural remanent magnetization and thermomagnetic properties of the Allende meteorite. Earth Planet. Sci. Lett., **17**, 120–128.

GUS'KOVA, YE. G. (1972): Magnetic Properties of Meteorites. Leningrad, Nauka Press, 143 p. (English translation, NASA TT F792, 1976).

LARSON, E. E., WATSON, D. E., HERNDON, J. M. and ROWE, M. W. (1973): Partial A. F. demagnetization studies of 40 meteorites. J. Geomagn. Geoelectr., **25**, 331–338.

NAGATA, T. and SUGIURA, N. (1975): Notes on magnetic properties of the Yamato meteorites. Mem. Natl Inst. Polar Res., Spec. Issue, **5**, 91–110.

NAGATA, T. and SUGIURA, N. (1976): Paleomagnetic field intensity derived from meteorite magnetization. Phys. Earth Planet. Inter., **13**, 373–393.

NAGATA, T., SUGIURA, N., and SCHWERER, F. C. (1976): Magnetic properties of Yamato-73-04 and Yamato-73-07 meteorites. Mem. Natl Inst. Polar Res., Ser. C, **10**, 12–29.

STACEY, F. D., LOVERING, J. F. and PARRY, L. G. (1961): Thermomagnetic properties, natural magnetic moments and magnetic anisotropies of some chondritic meteorites. J. Geophys. Res., **66**, 1523–1534.

SUGIURA, N. (1977): On the origin of NRM in stony meteorites. Ph. D. Thesis. Tokyo Univ., 156 p.

WEAVING, B. (1962): The magnetic properties of the Brewster meteorites. Geophys. J., **7**, 203–210.

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