PALEOMAGNETISM OF STONY METEORITES

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Abstract: The paleointensity for a howardite, an ulerite and three diogenites has been determined. By referring to these five values of paleointensity, the paleointensity for 6 achondrites is determined by comparing their NRM with the saturation IRM (Fuller's method). The paleointensity (F_0) for achondrites thus determined is represented by $F_0=(0.11\pm0.02)$Oe.

The paleointensity for Allende C_3-chondrite is examined from various standpoints. Four other C-chondrites having reasonably stable NRM also are paleomagnetically examined. The average paleointensity for the C-chondrites is $F_0=(1.02\pm0.09)$Oe.

Ordinary chondrites have a less stable NRM so that the evaluated paleointensity for ordinary chondrites is less reliable. The paleointensity for comparatively stable ordinary chondrites ranges from 0.1 to 0.4 Oe.

1. Introduction

Paleomagnetic studies of the natural remanent magnetization (NRM) of meteorites have been interested specifically in relation to the early solar system magnetic field (STACEY *et al.*, 1961; WEAVING, 1962; GUS'KOVA, 1963; BANERJEE and HARGRAVES, 1972; BUTLER, 1972; GUS'KOVA, 1972; BRECHER and ARRHENIUS, 1974; NAGATA and SUGIURA, 1977). Recent efforts to retrieve a large number of meteorites from Antarctica (NAGATA, 1975; CASSIDY *et al.*, 1978) have resulted in collecting about 1600 new pieces of meteorites. Since these Antarctic meteorites have been treated with extreme scientific care to minimize possible chemical and magnetic contaminations in the courses of their collection, transportation, storage and subdivision, these samples can be considered sufficiently reliable for the purpose of paleomagnetic studies. Using these Antarctic meteorites, therefore, a systematic paleomagnetic study is under way at present.

Iron, stony-iron and stony meteorites have NRM in general. The intensity and direction of NRM of carbonaceous chondrites are the most stable against the AF-demagnetization, and those of achondrites are reasonably stable, whereas those of many enstatite chondrites and ordinary chondrites (H-, L- and LL-chondrites) are poorly stable, though some ordinary chondrites have a reasonably stable NRM. NRM of iron meteorites is reasonably stable, but its acquisition mechanism is subjected to a particular condition independent of an ambient magnetic field, as discussed later. On the contrary, stony-iron meteorites generally have poorly stable NRM (LARSON *et al.*, 1973; NAGATA, 1979a).

Carbonaceous chondrites containing a fair abundance of volatile substance are believed to be formed at the very early stage of the primordial solar system and thermally metamorphosed only very little since their formation time. It is most likely that carbonaceous chondrites were formed as planetesimals (less than 10 km in linear scale) or parts of planetesimals from cosmic dusts and have never experienced to be parts of any primordial planet (larger than 10^2 km in linear scale) in their life to date. Therefore, the observed stable NRM of carbonaceous chondrites may not be attributable to a planetary dynamo magnetic field, but it would represent the solar wind magnetic field at the very active protosun stage or a magnetic field with the primordial solar nebula surrounding the protosun, probably at the T-Tauri stage of our solar system (LEVY and SONETT, 1978).

The observed reasonably stable NRM of achondrites also may be of interest from another viewpoint. It is almost certain that achondrites are the products of differentiation and/or brecciations of primordial planets, and they may represent a silicate crust and/or mantle after melting and differentiation of each primordial planet into a metal or iron-stony core and silicate layers. If so, the achondrite NRM could represent possible dynamo magnetic fields of primordial planets. As for the stable NRM of iron meteorites, BRECHER and ALBRIGHT (1977) have experimentally demonstrated that a cooling procedure of an octahedrite in non-magnetic space can result in an acquisition of a stable remanent magnetization of intensity equivalent to that of TRM acquired in a magnetic field of several Oersteds. The acquisition of the stable remanence in non-magnetic space is interpreted as due to the crystallographically regular orientation of kamacite phase domains in the course of Widmannstätten structure growth. It can be concluded from this result that the stable NRM of iron meteorites is not reliable as an indicator of an ambient magnetic field for their formation in the extraterrestrial space.

In general, NRM's of E-, H-, L- and LL-chondrites and stony-iron meteorites are less stable compared with those of carbonaceous chondrites and achondrites. It has been experimentally demonstrated, however, that some selected ordinary chondrites have a considerably stable NRM against the AF-demagnetization. These stable NRM's of ordinary chondrites may be worthwhile to be analyzed in detail. It must be considered, however, that these ordinary chondrites were seriously metamorphosed during their formation processes so that the identification of NRM acquisition mechanism for these chondrites should be more complicated than that for carbonaceous chondrites and achondrites.

An important problem regarding NRM of meteorites is the fusion crust magnetization which is attributable to TRM and/or CRM of the skin layer of meteorites acquired on their entry into the earth's atmosphere (WEAVING, 1962; BUTLER, 1972; NAGATA and SUGIURA, 1977; NAGATA, 1979b). The anomalously magnetized skin layer is about 1 mm thick for stony meteorites and about 20 mm thick for iron meteorites. In discussing the paleomagnetic field in the extraterrestrial space on the basis of meteoritic NRM, therefore, the surface skin layer having the anomalous magnetization must be completely removed and the uniform interior NRM only must be examined.

In the present report, paleomagnetic studies on achondrites and carbonaceous chondrites will be specifically emphasized because of the above-mentioned reason.

2. Paleointensity for Achondrites

The content of ferromagnetic metal is generally small in achondrites so that their NRM intensity also is small in general. As already pointed out, the paleo-intensity study of achondrites will be of special interest in association with a possible dynamo magnetic field of primordial planet. For the purpose of paleomagnetic studies, therefore, 11 achondrites (6 diogenites, 2 eucrites and 1 howardite) of the Yamato meteorite collection and an eucrite and an ulerite of the Allan Hills meteorite collection have been selected, because the mineralogical structures of these achondrites have been examined in fair detail (OKADA, 1975; YAGI *et al.*, 1978; TAKEDA *et al.*, 1978; MIYAMOTO *et al.*, 1978; OLSEN *et al.*, 1978).

2.1. *Yamato-74013 (Diogenite)*

NRM of this diogenite is very stable against the AF-demagnetization with respect to both the intensity and direction, as represented by $I_n(200)/I_n(0)=0.87$ and $I_n(400)/I_n(0)=0.33$, where $I_n(0)$, $I_n(200)$ and $I_n(400)$ denote respectively the NRM intensities before the AF-demagnetization, after an AF-demagnetization up to 200 Oe peak and after an AF-demagnetization up to 400 Oe peak. Fig. 1 shows a diagram of NRM-lost versus ARM-gained for this diogenite in the standard

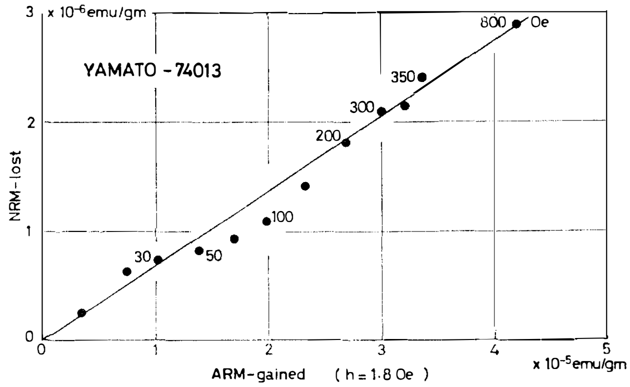

Fig. 1. Diagram of NRM-lost versus ARM-gained to determine the paleointensity for Yamato-74013 diogenite.

NRM-ARM method of paleointensity determination (*e.g.* STEPHENSON and COLLINSON, 1974). This experimental result indicates that the paleointensity for this achondrite is given by F_0=0.093 Oe.

2.2. Yamato-7307 (Howardite)

NRM of this howardite is reasonably stable against the AF-demagnetization, as indicated by $I_n(200)/I_n(0)=0.57$. From the Königisberger-Thellier experiment on this sample, the paleointensity is estimated as F_0=0.07 Oe, where the linear relationship between NRM-lost and TRM-gained holds up to a temperature T_0=240°C.

2.3. Yamato-74037 (Diogenite)

NRM of this diogenite also is reasonably stable as shown by $I_n(100)/I_n(0)=0.69$ and $I_n(200)/I_n(0)=0.35$. The paleointensity determination by the standard NRM-ARM method has given F_0=0.032 Oe.

2.4. Yamato-74648 (Diogenite)

NRM of this diogenite is reasonably stable as indicated by $I_n(100)/I_n(0)=0.89$ and $I_n(200)/I_n(0)=0.49$. The standard NRM-ARM method experiment has given a result of F_0=0.24 Oe.

2.5. Allan Hills-77257 (Ulerite)

NRM of this ulerite also is reasonably stable as shown by $I_n(100)/I_n(0)=0.61$ and $I_n(200)/I_n(0)=0.37$. The paleointensity of this ulerite is estimated by the standard NRM-ARM method, the result being given by F_0=0.089 Oe.

Table 1. NRM and paleointensity of achondrites.

Meteorite	I_s (emu/gm)	I_R (emu/gm)	$I_n(0)$ (emu/gm)	$I_n(100)$ (emu/mg)	F_0 (Oe)	$I_n(0)/I_R$
Yamato-7307 (Ho)	0.53	2.7×10^{-3}	6.3×10^{-6}	5.9×10^{-6}	0.07	2.3×10^{-3}
-74013 (Di)	0.17	1.2×10^{-3}	3.4×10^{-6}	3.2×10^{-6}	0.093	2.8×10^{-3}
-74037 (Di)	0.22	4.5×10^{-3}	4.6×10^{-6}	4.2×10^{-6}	0.032	1.0×10^{-3}
-74648 (Di)	0.20	7.5×10^{-3}	36.5×10^{-6}	32.5×10^{-6}	0.24	4.9×10^{-3}
Allan Hills-77257(Ul)	3.14	105.0×10^{-3}	256.0×10^{-6}	157.0×10^{-6}	0.089	2.4×10^{-3}
Yamato-692 (Di)	0.19	3.5×10^{-3}	15.4×10^{-6}	23.5×10^{-6}	(0.16)	4.4×10^{-3}
-74097 (Di)	0.32	4.0×10^{-3}	4.0×10^{-6}	3.2×10^{-6}	(0.036)	1.0×10^{-3}
-75032 (Di)	0.042	6.5×10^{-3}	4.2×10^{-6}	3.8×10^{-6}	(0.023)	0.65×10^{-3}
-74159 (Eu)	0.061	4.0×10^{-3}	22.6×10^{-6}	23.2×10^{-6}	(0.20)	5.7×10^{-3}
-74450 (Eu)	0.050	0.44×10^{-3}	1.3×10^{-6}	0.83×10^{-6}	(0.11)	3.0×10^{-3}
Allan Hills-7605(Eu)	0.076	0.84×10^{-3}	4.5×10^{-6}	2.1×10^{-6}	(0.19)	5.4×10^{-3}

Di=Diogenite, Ho=Howardite, Eu=Eucrite, Ul=Ulerite.

In Table 1, the paleointensities of 5 achondrites thus estimated are summarized together with their saturation magnetization (I_s), saturation remanence (I_R), $I_n(0)$ and $I_n(100)$. As suggested from its structure, an ulerite Allan Hills-77257 has extremely large values of I_s, I_R and $I_n(0)$ compared with those of diogenites, howardites and eucrites.

2.6. *Other achondrites*

NRM's of 3 other diogenites (Yamato-692, -74097 and -75032) and 3 eucrites (Yamato-74159 and -74450, and Allan Hills-76005) have been examined. As indicated by $I_n(0)$ and $I_n(100)$ values of these achondrites, summarized in Table 1, their NRM's are stable against the AF-demagnetization.

Although the paleointensity of these six achondrites have not yet been finally obtained, a comparison of the stable NRM with the saturation remanent magnetization (I_R) will be able to suggest the order of magnitude of the paleointensity, as demonstrated by FULLER (1974) for lunar materials. In Table 1, it will be observed that F_0 is roughly proportional to $I_n(0)/I_R$ for five achondrites whose F_0 values have been determined. Namely, $I_n(0)/I_R \simeq \alpha^2 F_0$, where α^2 is a constant

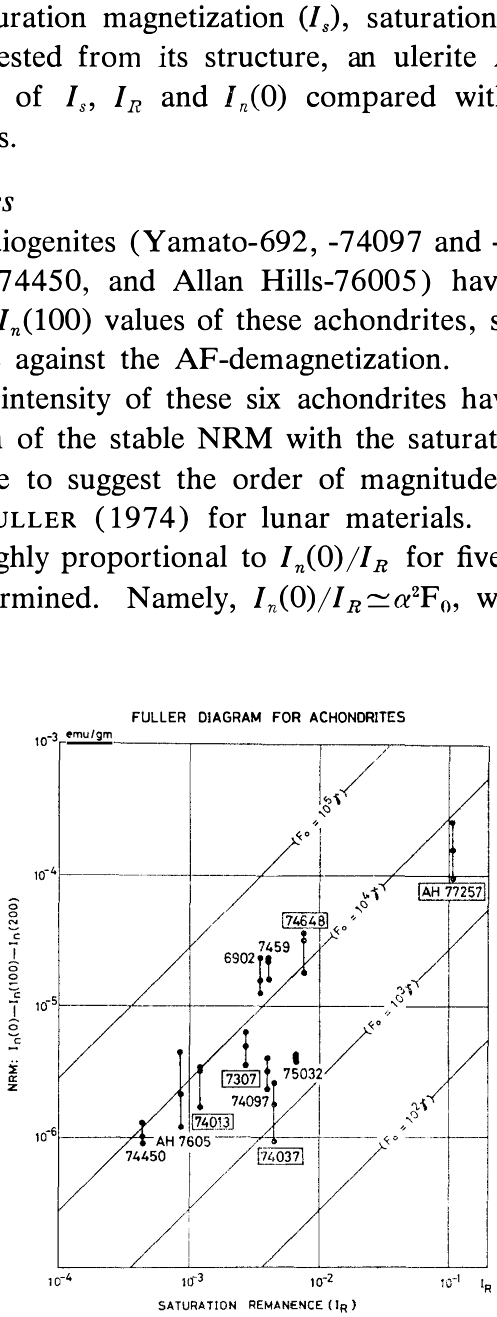

Fig. 2. Diagram of I_n (0), I_n (100) and I_n (200) of NRM versus saturation IRM (I_R) for 11 achondrites. Remarks: Numerals of sample show the number of Yamato meteorites. Number with AH of sample shows the number of Allan Hills meteorites. The sample number within a rectangular frame indicates the achondrite used for the calibration of α^2-value.

of a positive value. The average value of α^2 for the five achondrites is given by $\alpha^2=(0.028\pm0.004)\mathrm{Oe}^{-1}$. If this coefficient value is adopted, the paleointensity for the three diogenites and the three eucrites can be approximately estimated as given in parentheses in Table 1. The paleointensity of 11 achondrites thus estimated ranges from 0.023 Oe to 0.24 Oe, the average value of F_0 being given by $F_0=(0.11\pm0.02)$Oe.

Following the original diagram proposed by FULLER (1974) to present the relationship between I_n and I_R as a function of F_0, $I_n(0)$, $I_n(100)$ and $I_n(200)$ values are plotted against I_R-value for individual achondrites in Fig. 2.

3. Paleointensity for Carbonaceous Chondrites

The Yamato meteorite collection include two carbonaceous chondrites, *i.e.* Yamato-693(c) and Yamato-74662. Although NRM's of these two C-chondrites are reasonably stable against the AF-demagnetization, as represented by $I_n(100)/I_n(0)=0.56$ and $I_n(200)/I_n(0)=0.15$ for Yamato-693(c) and $I_n(100)/I_n(0)=0.88$ and $I_n(200)/I_n(0)=0.60$ for Yamato-74662, the paleointensity determination experiment on these carbonaceous chondrites has not yet been fully successful.

On the other hand, several other carbonaceous chondrites have been paleomagnetically studied by the writer and his colleague. The examined carbonaceous chondrites are Allende, Leoville and Karoonda.

3.1. *Allende* (C_3)

NRM of Allende C_3-chondrite has been studied in fair detail by several investigators (BANERJEE and HARGRAVES, 1972; BUTLER, 1972; BRECHER, 1977). NRM of Allende is extremely stable against the AF-demagnetization, as represented by $I_n(500)/I_n(0)=0.83$ (NAGATA and SUGIURA, 1977), $=0.87$ (BANERJEE and HARGRAVES, 1972), and $=0.63$ (BRECHER and ARRHENIUS, 1974). The paleointensity of Allende was examined with the Königisberger-Thellier method independently by BANERJEE and HARGRAVES (1972) and BUTLER (1972), on an assumption that the acquisition process of NRM is thermoremanence. In results of Banerjee and Hargraves' study, a linear relationship between the NRM-lost and the TRM-gained holds for a temperature range of 20~130°C, inconsistent data being obtained above 130°C. In results of BUTLER's experiment, the upper limit temperature (T_0) for the linear relationship is 150°C. The paleointensity (F_0) for Allende thus estimated for a temperature range below T_0 is (1.09 ± 0.08)Oe (BANERJEE and HARGRAVES, 1972) and (1.11 ± 0.14)Oe (BUTLER, 1972), as summarized in Table 2.

The paleointensity thus estimated represents an ambient magnetic field, in which Allende was cooled down from 130–150°C, acquiring TRM during the cooling process. However, NRM corresponding to TRM acquired during the cooling through the temperature range is only 1/3 or less of the total NRM. In

Table 2. Magnetic properties and paleointensity of Allende C_3-chondrite.

Investigator / Magnetic parameters	NAGATA and SUGIURA	BANERJEE and HARGRAVES	BUTLER	GUS'KOVA	BRECHER and ARRHENIUS	Unit
I_s	0.61	—	—	—	(0.48~0.73)	(emu/gm)
H_c	143	—	—	—	138±3	(Oe)
$I_n(0)$	2.7×10^{-4}	$(1.9\sim2.5)\times10^{-4}$	3.4×10^{-4}	—	$(2.2\sim3.4)\times10^{-4}$	(emu/gm)
$I_n(500)/I_n(0)$	0.83	0.87	—	—	0.63	
Θ_c	576, 620	620	610	—	—	(°C)
F_0	0.73	1.09±0.08	1.11±0.14	1.00±0.11	0.95 (0.25)	(Oe)

I_s: Saturation magnetization. H_c: Coercive force. $I_n(0)$: Original NRM intensity.
$I_n(500)$: Residual intensity of NRM after AF-demagnetizing up to 500 Oe peak.
Θ_c: Curie point. F_0: Paleointensity.

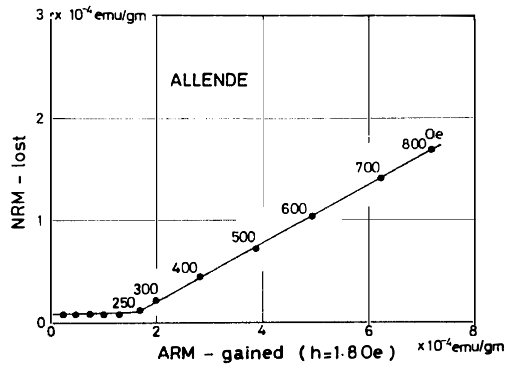

Fig. 3. Diagram of NRM-lost versus ARM-gained to determine the paleointensity for Allende C_3-chondrite.

the experimental process, mineralogical structure of ferromagnetic constituent in this C-chondrite is changed on heating above 130–150°C so that the acquisition mechanism for the major parts of NRM cannot be identified by the Königisberger-Thellier method.

An alternative method for determining the paleointensity in such a case would be the so-called NRM-ARM method (*e.g.* STEPHENSON *et al.*, 1974). As illustrated in Fig. 3, a linear relationship between the NRM-lost by the AF-demagnetization and the ARM-gained holds for an alternating magnetic field larger than 250 Oe (up to 800 Oe in this experiment). The range of linear relationship covers the majority of the total NRM. An evaluation of the paleointensity for NRM from data of NRM-ARM method experiment on an assumption that the NRM concerned is thermoremanence, a transformation factor(f) defined by

$$I(\mathrm{TRM})/I(\mathrm{ARM}) = fh(\mathrm{TRM})/h(\mathrm{ARM})$$

plays an essential role, where h(TRM) and h(ARM) are magnetic fields applied for the acquisitions of TRM and ARM respectively. STEPHENSON and COLLINSON (1974) obtained f=1.34 from experimental data on metallic grain assemblages and a lunar sample. We also have experimentally obtained f=1.3 on average from synthesized samples containing fine grains of iron of different sizes. Adopting f=1.3, the paleointensity for Allende on the TRM origin assumption is estimated as F_0=0.73 Oe, as given in Table 2.

GUS'KOVA (private communication) has recently examined NRM of Allende by Shashkanov-Metallova method (SHASHKANOV and METALLOVA, 1974), which is essentially based on ARM characteristics in comparison with the NRM micro-coercivity spectrum. Her result is represented by F_0=(1.00±0.11)Oe for Allende, as given in Table 2.

BRECHER (1977) also estimated the paleointensity for Allende with the aid of the so-called NRM-pTRM method. In comparison with the AF-demagnetization curve of pTRM acquired by cooling from 150°C with that of NRM, she has obtained F_0=0.95 Oe for $\tilde{H}<500$ Oe, and F_0=0.25 Oe for $\tilde{H}>500$ Oe, where $\tilde{H}$ denotes the AF-demagnetization field intensity. In the case of pTRM-NRM method, a determination of paleointensity is ambiguous if no unique linear relationship holds between the NRM-lost and the pTRM-lost caused by the AF-demagnetization.

Summarizing these five experimental results on NRM of Allende in Table 2, it may be concluded that the very stable NRM of Allende C_3-chondrite was acquired in a magnetic field of about 1 Oe by the TRM mechanism or a similar acquisition mechanism of remanence such as CRM. As shown in Table 2, the NRM intensities of different pieces of Allende independently measured by different investigators are in approximate agreement with one another and its coercive force (H_c) and NRM stability ($I_n(500)/I_n(0)$) are very high. In addition, the paleointensity values for Allende estimated by different investigators with the aid of different methods are in reasonably good agreement with one another, when possible errors in respective experiments are taken into account.

3.2. *Orgueil (C_1), Mighei (C_2), Leoville (C_3) and Karoonda (C_4)*

Observed values of I_s, H_c and Θ_c of four C-chondrites, Orgueil, Mighei, Leoville and Karoonda, are summarized in Table 3, where $I_n(0)$ and $I_n(200)/I_n(0)$ also are given. As indicated by $I_n(200)/I_n(0)$, NRM's of these four C-chondrites are considerably less stable against the AF-demagnetization than NRM of Allende C-chondrite. It would be considered therefore that the paleointensity of these chondrites

Table 3. Magnetic properties and paleointensity of Orgueil (C_1) Mighei(C_2), Leoville (C_3) and Karoonda (C_4).

Meteorite / Magnetic parameters	Orgueil (C_1)	Mighei (C_2)	Leoville (C_3)	Karoonda(C_4)	Unit
I_s	11.9	0.60	10.3	7.8	(emu/gm)
H_c	107	141	34	155	(Oe)
$I_n(0)$	2.0×10^{-4}	1.6×10^{-3}	4.4×10^{-3}	2.7×10^{-4}	(emu/gm)
$I_n(200)/I_n(0)$	0.26	0.17	0.10	0.08	
Θ_c	580	580	575	550	(°C)
F_0	0.67 * 1.36±0.09**	1.24±0.36**	0.97***	0.89***	(Oe)

* BANERJEE and HARGRAVES (1972). ** GUS'KOVA (private communication).
*** NAGATA and SUGIURA (1977).

is less reliable than that of Allende.

By the Königisberger-Thellier method, the paleointensity for Orgueil has been estimated as F_0=0.67 Oe with T_0=70°C (BANERJEE and HARGRAVES, 1972). GUS'KOVA (private communication) has recently examined the paleointensity for 3 pieces of Orgueil by the Shashkov-Metallova method, and has obtained F_0=(1.23–1.50)Oe, the average value being F_0=(1.36±0.09)Oe. Thus, the paleointensity for Orgueil also can be estimated to be about 1 Oe.

With the aid of the Shashkov-Metallova method, GUS'KOVA (private communication) has recently examined the paleointensity of 6 pieces of Mighei. The paleointensity of this meteorite thus evaluated ranges from 0.87 to 1.78 Oe, the average value being given by F_0=(1.24±0.36)Oe.

The paleointensity of Leoville has been estimated by NAGATA and SUGIURA (1977) with the aid of the Königisberger-Thellier method. Their results are represented by F_0=0.97 Oe with T_0=300°C.

SUGIURA and NAGATA have recently examined the pTRM characteristics of Karoonda in some detail, and have found from results of the NRM-pTRM paleointensity experiment that NRM of this C_4-chondrite is attributable to TRM corresponding to F_0=0.89 Oe and T_0=300°C.

The paleointensities of the four C-chondrites thus estimated are summarized in Table 3. Taking into consideration that the paleointensity values for Allende determined for its different specimens by different investigators with different experimental methods range from 0.7 to 1.1 Oe, it can be only concluded in Table 3 that the most plausible value of paleointensity for these C-chondrites is around 1 Oe.

In other words, the paleointensity values estimated from comparatively reliable

NRM's of five carbonaceous chondrites are all around $F_0=1$ Oe. We may conclude therefore that the ambient magnetic field for the formation of C-chondrites was about 1 Oe.

4. Paleointensity for Ordinary Chondrites

As already mentioned, a number of examined NRM's of ordinary chondrites are considerably less stable than those of achondrites and C-chondrites against the AF-demagnetization, $I_n(100)/I_n(0)$ becoming smaller than 0.1. However, some ordinary chondrites still have a considerably stable NRM. Results of paleointensity studies on the comparatively stable NRM's of ordinary chondrites will be summarized in the following.

Yamato-74191 L_3-chondrite possesses a stable NRM, as represented by $I_n(100)/I_n(0)=0.77$ and $I_n(300)/I_n(0)=0.50$. SUGIURA and NAGATA have examined NRM of this L-chondrite to evaluate the paleointensity by means of the standard NRM-ARM method. Their result is given by $F_0=0.13$ Oe for Yamato-74191.

NRM's of Fukutomi L_5-chondrite ($I_n(100)/I_n(0)=1.03$) and Yonozu $H_{4,5}$-chondrite ($I_n(100)/I_n(0)=1.00$) also can be considered reasonably stable. By the Königisberger-Thellier method NAGATA and SUGIURA (1977) estimated their paleointensity as $F_0=0.10$ Oe with $T_0=400°C$ for Fukutomi and $F_0=0.18$ Oe with $T_0=470°C$ for Yonozu.

WEAVING (1962) examined a stable NRM of Brewster L_6-chondrite, which is represented by $I_n(100)/I_n(0)=0.93$ and $I_n(300)/I_n(0)=0.40$. By comparing TRM with NRM, the paleointensity for Brewster has been estimated to be about 0.1 Oe.

There are some other available data of the paleointensity for ordinary chondrites. For example, the paleointensities for Dalgety Down L_4-chondrite and Seminole H_4-chondrite have been evaluated by the Königisberger-Thellier method to be 0.68 Oe and 0.39 Oe respectively (NAGATA and SUGIURA, 1977). However, NRM's of these two ordinary chondrites cannot be considered sufficiently stable, as indicated by $I_n(100)/I_n(0)=0.049$ for Dalgety Down and $I_n(100)/I_n(0)=0.031$ for Seminole.

In the present summary of the paleointensity data of meteorites, only the stable NRM of stony meteorites defined by a criterion of $I_n(100)/I_n(0)>0.1$ is concerned. However, the paleointensity data for ordinary chondrites obtained by various investigators are summarized in Table 4 for the purpose of their comparison with the paleointensities for achondrites and carbonaceous chondrites, though the stability of their NRM's against the AF-demagnetization has not been clearly examined.

In Table 4, the paleointensity values of the four ordinary chondrites on the top lines may be considered comparatively reliable. If all listed values are accepted, it may be concluded that the paleointensity for ordinary chondrites ranges mostly from 0.1 to 0.4 Oe. In other words, the paleointensity for ordinary chondrites takes the intermediate values between that of achondrites ($F_0 \lesssim 0.2$ Oe) and that

Table 4. Paleointensity for ordinary chondrites.

Meteorite	Paleointensity (Oe)	Method	Investigator
Yamato-74191 (L_4)	0.13	NRM/ARM	(0)
Fukutomi (L_5)	0.10	(K−T), T_0=400°C	(3)
Brewster (L_6)	0.1	NRM/TRM	(2)
Yonozu ($H_{4,5}$)	0.18	(K−T), T_0=470°C	(3)
Farmington (L_5)	0.18	NRM/TRM	(1)
Mt. Bronn (H_6)	0.25	NRM/TRM	(1)
Dalgety Down (L_4)	0.68	(K−T), T_0=470°C	(3)
Seminole (H_4)	0.39	(K−T), T_0=350°C	(3)
Rakovka (L_6)	0.4	NRM/TRM	(4)
Morduinovka (L)	0.4	NRM/TRM	(4)
Okhansk (H_4)	0.3	NRM/TRM	(4)
Paltusk (H_4)	0.21	NRM/TRM	(4)
Mezö-Madaras (L_3)	0.13	NRM/TRM	(5)
Elenovka (L)	0.19	NRM/TRM	(5)
Parvomayski Poselok (L)	0.12	NRM/TRM	(5)
Tarbagatay (L)	0.27	NRM/TRM	(5)
Orlovka (H)	0.25	NRM/TRM	(5)

(K−T): Königisberger-Thellier method
(0): Present work. (1): STACEY *et al.* (1961). (2): WEAVING (1962). (3): NAGATA and SUGIURA (1977). (4): GUS'KOVA (1963). (5): GUS'KOVA (1972).

of carbonaceous chondrite (F_0~1 Oe).

5. Magnetic Fields in the Early Solar System

It may be provisionally concluded from the results of paleomagnetic studies of three different groups of stony meteorites that the paleointensity is less than 0.2 Oe for achondrites, about 1 Oe for carbonaceous chondrites, and 0.1–0.4 Oe for ordinary chondrites.

A genetic relationship among the principal groups of stony meteorites suggests that carbonaceous chondrites represent the first products owing to the accretion of cosmic dusts as the planetesimals in the primordial solar nebula and ordinary chondrites are intermediate products caused by the thermal metamorphism of carbonaceous chondrites, while achondrites are the final products owing to the differentiation within meteorite parent planets (RINGWOOD, 1961). It has been shown on the other hand that all kinds of meteorites ranging from the most primordial carbonaceous chondrites to the most differentiated achondrites were formed during a period of less than 2×10^7 years about 4.5×10^9 years ago (PODOSEK, 1970). Then, the paleointensities for the three groups of stony meteorites may represent the magnetic fields at places and times where and when respective stony meteorites were formed in the solar nebula about 4.5×10^9 years ago.

As for the magnetic fields in the early solar system, LEVY and SONETT (1978) have pointed out two possibilities, *i.e.* (a) primordial solar wind magnetic field and a solar nebular dynamo. According to them, it is probable to assume the presence of a magnetic field of 1 Oe at 3 AU in distance from the sun if the solar wind speed was 3×10^7 cm/s, the solar spin rate was about a hundred times its present value and the solar surface magnetic field was about 10^3 Oe. Both the solar spin rate and the solar surface magnetic field will decrease with time. Then it will also be probable to assume that the magnetic field at 3 AU in the solar wind decreased from $F_0=1$ Oe to $F_0\leq0.1$ Oe during 2×10^7 years. The conclusion of present studies of the meteorite paleointensity that $F_0=1$ Oe for C-chondrite, $F_0=0.1$–0.4 Oe for ordinary chondrites and $F_0\lesssim0.2$ Oe for achondrites might then be attributable to the hypothetical decrease of the solar wind magnetic field.

As LEVY and SONETT pointed out, however, a significant difficulty in the solar wind field hypothesis for the meteorite paleointensity is concerned with the geometrical relation between the solar wind field direction and the direction of meteorite remanence. During the process of acquisition of TRM or CRM, the direction of affecting magnetic field must be kept constant with respect to the meteorite concerned. The solar wind magnetic field of a three dimensional Archimedian spiral configuration may not be regarded approximately constant with respect to the relative direction to a meteorite which is making a Kepler orbiting motion around the sun. Since the orbiting meteorite might be spinning also, however, the magnetic field component along the spinning axis alone may have affected the meteorite as a unidirectional field. If there were no reversal of the solar wind magnetic field component along the spinning axis, therefore, we may be able to expect that an orbiting and spinning meteorite could acquire TRM or CRM.

The second possibility pointed out by LEVY and SONETT is a solar nebular dynamo. That is, turbulent gas motions in a differentially rotating nebula can produce a hydromagnetic dynamo, and thereby generate a large-scale magnetic field, if the electric conductivity of the gas is sufficiently high. An essential point in this solar nebular dynamo model will be a sufficiently large electric conductivity of the nebula gas. Considering the ionization produced by the decay of ^{26}Al in a preplanetary nebula gas of 3×10^{-10} gm/cm^2 in pressure and 200°K in temperature, LEVY and SONETT have estimated that the electric conductivity is about 10^3 s^{-1}, which is sufficiently large for activating and maintaining the hypothetical nebular dynamo. Thus, the characteristic maximum magnetic field intensity evaluated by them is of the order of 5–10 Oe.

Since stationary, axisymmetric fields including a dipole-like field are the most easily excited modes of such a dynamo, the most effective magnetic field for a spinning and orbiting body will be a unidirectional field which is normal to the nebular disk.

In the case of this solar nebula dynamo, the generated magnetic field should be weakened in accordance with a decrease in the gas electric conductivity owing to the recombination of ionized gas and the decay of ionization source, ^{26}Al. The decay constant of the nebula dynamo has not yet been estimated. Since the half decay period of ^{26}Al is only 7.4×10^5 years, however, the whole life of the nebula dynamo could not be much longer than 10^6 years. Thus, a magnetic field generated by the hypothetical nebula dynamo may have decayed from the initial value of 5–10 Oe to zero during several million years.

In regard to the paleointensity for achondrites, another possibility that the ambient magnetic field during their formation process was due to a dynamo within the fluidal metallic core of their parent planet cannot be rejected. It does not seem possible at present, however, to discuss some details of such a primordial planetary dynamo.

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