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# MAGNETIC ANALYSIS OF ANTARCTIC CHONDRITES ON THE BASIS OF A MAGNETIC BINARY SYSTEM MODEL

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***Abstract:*** Ordinary chondrites often have extremely large values of their remanence coercive force ($H_{RC}$) while their coercive force ($H_C$) is not particularly large, $H_{RC}/H_C$ often amounting to a magnitude larger than 30. Since $H_{RC}/H_C$ of ferromagnetic materials is generally smaller than 5, the observed large values of chondrites are considered anomalous.

A magnetic binary system model consisting of (a)-component having large $H_C$ and $H_{RC}$ values and (b)-component having small $H_C$ and $H_{RC}$ values can approximates the anomalously large value of $H_{RC}/H_C$. Using the magnetic binary system model, Antarctic chondrites having anomalously large values of $H_{RC}/H_C$ are analyzed; metallic constituents in these chondrites are decomposed into (a)-component with $H_C \gtrsim 1000$ Oe and (b)-component with $H_C \lesssim 30$ Oe. Interest from a viewpoint of meteoritics may be concerned with following results of the analysis.

(i) With the aid of thermomagnetic analysis and other methods, the high coercivity component (a) is identified to tetrataenite which has an extremely large value of $H_C$, while the absolute majority of (b)-component comprises relatively large grains of kamacite of multi-domain structure.

(ii) Metallic fine grains in both chondrules and matrix of ALH-769 (L6) chondrite are composed of statistically same tetrataenite and kamacite. This result suggests that both chondrules and matrix were extremely slowly cooled down together through 320°C in the final process of the thermal history of this chondrite.

## 1. Introduction

The ratio of remanence coercive force ($H_{RC}$) to coercive force ($H_C$) of an assembly of randomly oriented ferromagnetic (or ferrimagnetic) particles of nearly same composition and structure, which are non-interactively dispersed in non-magnetic matrix, such as natural rocks, generally ranges between about 1.2 and about 5. $H_{RC}/H_C = 1.2–2$ corresponds to a case that the magnetic particles have a considerably large uniaxial magnetic anisotropy (WOHLFARTH, 1963), such as due to the shape anisotropy of single-domain particles or the crystal anisotropy of tetrataenite in meteorites. On the other hand, $H_{RC}/H_C = 4–5$ corresponds to a case that the magnetic particles are comparatively large multi-domain grains having a weak magnetic anisotropy, such as magnetite and titanomagnetite in terrestrial rocks or kamacite and disordered taenite in meteorites. Most terrestrial igneous, metamorphic and sedimentary rocks satisfy the condition of $1.2 \lesssim H_{RC}/H_C \lesssim 5.0$. (*e.g.* NAGATA and CARLETON, 1987). As shown in Fig. 1, however, $H_{RC}/H_C$ values of the majority (*i.e.* >71%) of ordinary chondrites exceed 8, $H_{RC}/H_C$

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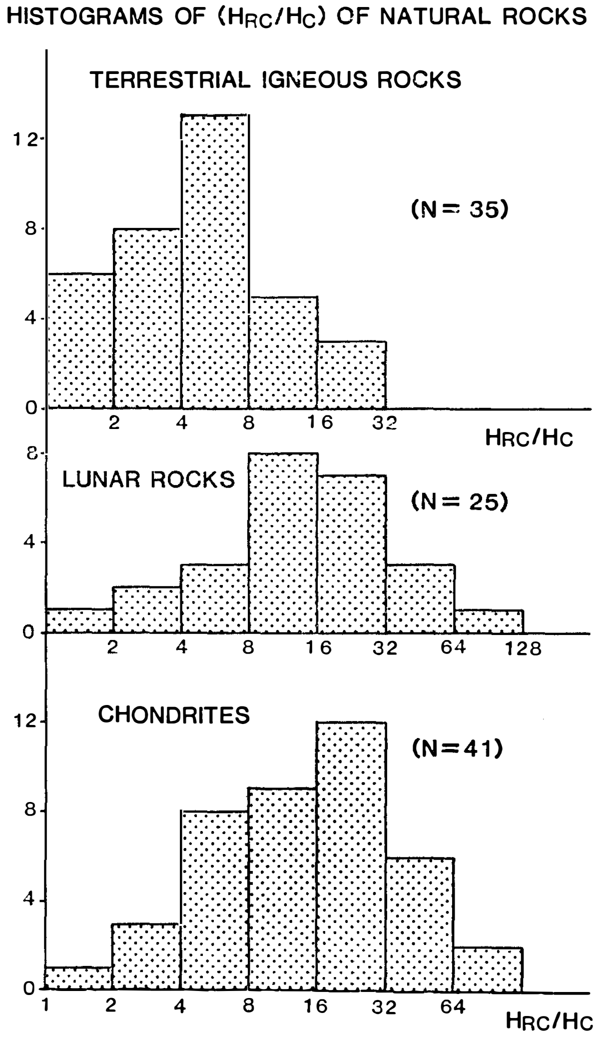

*Fig. 1. Histogram of $H_{RC}/H_C$ of terrestrial igneous rocks, lunar rocks and chondrites. $H_{RC}/H_C$ values in logarithmic scale. N: number of measured rock samples.*

values of 20% of the examined chondrites being larger than 32.

According to a theory of a magnetic binary system model consisting of a magnetically hard component (a) and a soft component (b) (NAGATA and CARLETON, 1987), on the other hand, a decreasing rate of $H_{RC}$ of a binary system with a decrease of (a)-component content is extremely small, whereas a decreasing rate of $H_C$ with the same decrease of (a)-component content is much large, as far as (a)-component content is not very small. Thus, $H_{RC}/H_C$ of a binary system, which is equal to $H_{RC}^{(a)}/H_C^{(a)}$ for the perfect (a) component and equal to $H_{RC}^{(b)}/H_C^{(b)}$ for the perfect (b)-component, takes its maximum value for a certain small value of mixing rate ($m$) of (a)-component in a binary system. If $H_C^{(a)}$ is very large compared with $H_C^{(b)}$, and therefore $H_{RC}^{(a)} \gg H_{RC}^{(b)}$ also, the maximum value of $H_{RC}/H_C$ of the binary system becomes large, being roughly proportional to $H_C^{(a)}/H_C^{(b)}$, while both $H_{RC}^{(a)}/H_C^{(a)}$ and $H_{RC}^{(b)}/H_C^{(b)}$ are kept invariant.

The observed anomalously large values of $H_{RC}/H_C$ of chondrites may therefore be interpreted as due to coexistence of a magnetically high coercivity (hard) component (a) having large values of $H_{RC}{}^{(a)}$ as well as $H_C{}^{(a)}$ and a low coercivity (soft) component (b) having small values of $H_C{}^{(b)}$ and $H_{RC}{}^{(b)}$. In the present work, Antarctic ordinary chondrites, which have anomalously large values of $H_{RC}/H_C$, will be analyzed with the aid of the proposed magnetic binary system model for the purpose of quantitatively identifying possible magnetic components in these chondrites.

## 2. Outline of a Magnetic Binary System Model

An outline of a magnetic binary system model proposed by NAGATA and CARLETON (1987) is as follows. Consider a magnetic binary system which is composed of 100 m% of (a)-component particles characterized by saturation magnetization $=I_S{}^{(a)}$, saturated remanent magnetization $=I_R{}^{(a)}$, $H_C{}^{(a)}$ and $H_{RC}{}^{(a)}$, and $100(1-m)\%$ of (b)-component particles characterized by $I_S{}^{(b)}$, $I_R{}^{(b)}$, $H_C{}^{(b)}$ and $H_{RC}{}^{(b)}$, where $H_C{}^{(a)}>H_C{}^{(b)}$ and $H_{RC}{}^{(a)}>H_{RC}{}^{(b)}$. In the present binary system model, the distribution of (a) and (b) particles, which are uniformly dispersed in non-magnetic matrix, are assumed to be so small that the magnetic interaction among individual magnetic particles is negligibly small.

In the case that (a)-component is represented by magnetic particles having a uniaxial magnetic anisotropy and (b)-component by those of multi-domain structure of nearly spherical shape, various experimental results are summarized, with reasonable theoretical justification, as

$$H_{RC}{}^{(a)}/H_C{}^{(a)} \equiv A \simeq 1.5\text{–}2,\quad H_{RC}{}^{(b)}/H_C{}^{(b)} \equiv B \simeq 4\text{–}5,\ \text{and}\ I_R{}^{(a)}/I_S{}^{(a)} \equiv \alpha \simeq 0.5,$$

while $I_R{}^{(b)}/I_S{}^{(b)} \equiv \beta$ is given by $\beta=0.002\text{–}0.003$ for Fe-Ni metals in meteorites and $\beta=0.02\text{–}0.04$ for titanomagnetites in terrestrial rocks. Then, noting saturation magnetization and saturated remanent magnetization of the binary system by $I_S$ and $I_R$ respectively, the mixing rate of (a)-component, $m$, is given by

$$m=\frac{(I_R/I_S-\beta)I_S{}^{(b)}}{(\alpha-I_R/I_S)I_S{}^{(a)}+(I_R/I_S-\beta)I_S{}^{(b)}}\,. \tag{1}$$

As $I_S{}^{(a)}$ and $I_S{}^{(b)}$ can be reasonably well estimated from observed qualification of the magnetic particles concerned, $m$ can be evaluated with the aid of eq. (1).

$H_C$ is defined by $I(H=H_C)=0$ in the course of magnetization by $H$ after magnetizing up to the saturation into the opposite direction, where $I(H)$ denotes magnetization due to $H$.

$$I(H=0)=I_R,\ I(H=H_C)=0\ \text{and}\ \left|\frac{\partial I}{\partial H}\right|_{H=0}<\left|\frac{\partial I}{\partial H}\right|_{H=H_C},$$

are necessary conditions for $I(H)$ characteristics. Then, the simplest possible expression of $I(H)$ may be given by

$$I(H)=I_R\left(1-\frac{H_C H+\varepsilon H^2}{(1+\varepsilon)H_C^2}\right). \tag{2}$$

It seems further that $\varepsilon=1$ in eq. (2) can satisfactorily approximate most experimentally observed $I(H)$ *vs.* $H$ curves for terrestrial rocks and meteorites.

$H_{\mathrm{RC}}$ is defined by $I_{\mathrm{D}}(H_{\mathrm{RC}})=0$, where $I_{\mathrm{D}}(H)$ denotes the DC demagnetization remanence acquired after saturation in one direction and the subsequent application of $H$ in the opposite direction. Noting remanent magnetization acquired after an application of DC field $H$ by $I_{\mathrm{r}}(H)$, $I_{\mathrm{D}}(H)$ is given (WOHLFARTH, 1958) by

$$I_{\mathrm{D}}(H)=I_{\mathrm{R}}-2I_{\mathrm{r}}(H), \qquad (3)$$

and $I_{\mathrm{r}}(H)$ must satisfy the following 3 conditions, *i.e.*

$$I_{\mathrm{r}}(0)=0, \qquad I_{\mathrm{r}}(H_{\mathrm{RC}})=I_{\mathrm{R}}/2, \qquad I_{\mathrm{r}}(\infty)=I_{\mathrm{R}}. \qquad (4)$$

A possible simple empirical formula of $I_{\mathrm{r}}(H)$, which can satisfy the three conditions and reasonably well fit experimental data is expressed by

$$I_{\mathrm{r}}(H)=\frac{1}{2}\left(\frac{H}{H_{\mathrm{RC}}}\right) \text{ for } H\leqq H_{\mathrm{RC}}, \quad I_{\mathrm{r}}(H)=I_{\mathrm{R}}\left(1-\frac{H_{\mathrm{RC}}}{2H}\right) \text{ for } H\geqq H_{\mathrm{RC}}. \qquad (5)$$

The empirical formulae of $I_{\mathrm{r}}(H)$ expressed by eq. (5) can approximately represent observed $I_{\mathrm{r}}(H)$ *vs.* $H$ curves except for a weak field range from zero to about 30 Oe, where $I_{\mathrm{r}}(H)$ roughly follows Rayleigh's law.

For a magnetic binary system which is generally expressed by

$$I(H)=mI^{(\mathrm{a})}(H)+(1-m)I^{(\mathrm{b})}(H), \qquad (6)$$

$H_{\mathrm{C}}/H_{\mathrm{C}}^{(\mathrm{a})}\equiv\zeta$ and $H_{\mathrm{RC}}/H_{\mathrm{RC}}^{(\mathrm{a})}\equiv\zeta^*$ are algebraically expressed by

$$\{mY+(1-m)\eta^2\}\zeta^2+\{mY+(1-m)\eta\}\zeta-2\{mY+(1-m)\}=0, \qquad (7)$$

$$mY\eta^*(\zeta^*)^2-\{mY-(1-m)\}\eta^*\zeta^*-(1-m)=0, \qquad (8)$$

where $Y\equiv I_{\mathrm{R}}^{(\mathrm{a})}/I_{\mathrm{R}}^{(\mathrm{b})}$, $\eta\equiv H_{\mathrm{C}}^{(\mathrm{a})}/H_{\mathrm{C}}^{(\mathrm{b})}$ and $\eta^*\equiv H_{\mathrm{RC}}^{(\mathrm{a})}/H_{\mathrm{RC}}^{(\mathrm{b})}$. Since $Y=(\alpha/\beta)(I_{\mathrm{S}}^{(\mathrm{a})}/I_{\mathrm{S}}^{(\mathrm{b})})$ and $\eta^*=(\mathrm{A}/\mathrm{B})\eta$,

$$H_{\mathrm{RC}}/H_{\mathrm{C}}=A(\zeta^*/\zeta), \qquad (9)$$

is a function of a variable $\eta$ only with parameters $m$ and $Y$ which have already been estimated. Solving eqs. (7) and (8) for positive values of $\zeta$ and $\zeta^*$, respectively, as functions of $\eta$ (or $\eta^*$), the value of $\eta$ satisfying the required relation eq. (9) between $\zeta^*/\zeta$ and observed $H_{\mathrm{RC}}/H_{\mathrm{C}}$ should be identical to $H_{\mathrm{C}}^{(\mathrm{a})}/H_{\mathrm{C}}^{(\mathrm{b})}$, which can give rise to evaluations of $H_{\mathrm{C}}^{(\mathrm{a})}$, $H_{\mathrm{RC}}^{(\mathrm{a})}$, $H_{\mathrm{C}}^{(\mathrm{b})}$ and $H_{\mathrm{RC}}^{(\mathrm{b})}$ separately.

Applicability of the present magnetic binary system model on an analysis of rock samples characterized by $I_{\mathrm{S}}$, $I_{\mathrm{R}}$, $H_{\mathrm{C}}$ and $H_{\mathrm{RC}}$ to decompose into $m$, $H_{\mathrm{C}}^{(\mathrm{a})}$, $H_{\mathrm{RC}}^{(\mathrm{a})}$, $H_{\mathrm{C}}^{(\mathrm{b})}$ and $H_{\mathrm{RC}}^{(\mathrm{b})}$ of two components, has been demonstrated with several examples (NAGATA and CARLETON, 1987).

## 3. Analyses of Antarctic Chondrites Based on $H_{\mathrm{RC}}/H_{\mathrm{C}}$

Table 1 shows typical examples of observed magnetic hysteresis parameters, $I_{\mathrm{S}}$, $I_{\mathrm{R}}$, $H_{\mathrm{C}}$ and $H_{\mathrm{RC}}$, of Antatctic chondrites which have $H_{\mathrm{RC}}/H_{\mathrm{C}}$ larger than 10 (NAGATA and

*Table 1. Magnetic hysteresis parameters and thermomagnetic parameters of Antarctic chondrites.*

| Chondrite | $I_S$ (emu/g) | $I_R$ (emu/g) | $I_R/I_S$ | $H_C$ (Oe) | $H_{RC}$ (Oe) | $H_{RC}/H_C$ | $H^{+}_{\alpha\to\gamma}$ (°C) | $H^{+}_{\gamma\to\alpha}$ (°C) | $\theta_C$ (°C) |
|---|---|---|---|---|---|---|---|---|---|
| Y-7301 (H4) | 15.0 | 0.14 | 0.0093 | 16 | 1700 | 106.3 | 755 | 660 | 577 |
| Y-74647 (H4-5) | 27.9 | 0.34 | 0.0122 | 14 | 1080 | 77.1 | 753 | 660 | 561 |
| Y-74191 (L3) | 6.8 | 0.22 | 0.0324 | 30 | 1330 | 44.3 | 766 | 670 | 558 |
| Y-74354 (L) | 21.8 | 0.71 | 0.0326 | 66 | 2620 | 39.7 | 750 | 644 | 542 |
| Y-74362 (L) | 8.1 | 0.27 | 0.0333 | 38 | 1300 | 34.2 | 750 | 645 | 559 |
| ALH-77260 (L3) | 5.20 | 0.16 | 0.0308 | 86 | 1150 | 13.4 | 775 | 690 | 570 |
| ALH-769 (L6) | | | | | | | | | |
| (A-0) | 8.35 | 0.52 | 0.0623 | 160 | 2100 | 12.1 | 770 | 680 | 575 |
| (A-1) | 9.73 | 0.34 | 0.0349 | 92 | 2700 | 29.3 | — | — | — |
| (A-2) | 9.80 | 0.37 | 0.0378 | 110 | 2470 | 22.5 | 764 | 642 | 575 |
| (A-3) | 18.1 | 0.31 | 0.0171 | 35 | 1879 | 53.7 | — | — | — |

SUGIURA, 1976; NAGATA and FUNAKI, 1982, 1987). The $\alpha\to\gamma$ and $\gamma\to\alpha$ transition temperatures of kamacite phase, $\Theta_{\alpha\to\gamma}$ and $\Theta_{\gamma\to\alpha}$ respectively, and apparent Curie point of taenite phase, $\theta_C$, of the chondrites also are given in Table 1. Kamacite phase indicated by $\Theta_{\alpha\to\gamma}$ and $\Theta_{\gamma\to\alpha}$ is the major component of metal and taenite phase (including tetrataenite) represented by $\theta_C$ is the minor component of metal in these chondrites. For ALH-769 L6 chondrite, the magnetic hysteresis parameters of 4 specimens are specifically measured for the purpose of examining partition characteristics of magnetic components among chondrules, metallic grains and matrix in this chondrite, as will be discussed later.

The observed values of $I_R/I_S$, $H_C$ and $H_{RC}$ of these chondrites are analyzed on the basis of the present magnetic binary system model, by assuming that the high coercivity component (a) is represented by taenite particles having a uniaxial anisotropy while the low coercivity component (b) by kamacite particles having multi-domain structure. Then, $A \equiv H_{RC}^{(a)}/H_C^{(a)} = 1.5$ and $B \equiv H_{RC}^{(b)}/H_C^{(b)} = 4.0$ may be assumed with probable error less than 20%.

$\alpha \equiv I_R^{(a)}/I_S^{(a)} = 0.5$ is generally acceptable with probable error less than 10%, while $\beta \equiv I_R^{(b)}/I_S^{(b)} = 0.002$–$0.003$ for Fe-Ni metals in meteorites (NAGATA and CARLETON, 1987). In the case of ferromagnetic Fe-Ni metals with small amounts of Co and P in meteorites, $I_S^{(a)} \simeq 160$ emu/g for taenites and $I_S^{(b)} \simeq 210$ emu/g for kamacite may be considered reasonable assumptions.

In the present analysis, therefore, $I_S^{(a)} = 160$ emu/g, $I_S^{(b)} = 210$ emu/g, $A = 1.5$, $B = 4.0$, $\alpha = 0.5$ and $\beta = 0.003$ in Model I and $\beta = 0.002$ in Model II are assumed throughout all numerical calculations.

Table 2 summarizes calculated values of $m$, $H_C^{(a)}$, $H_{RC}^{(a)}$, $H_C^{(b)}$ and $H_{RC}^{(b)}$ for Models I and II of the magnetic binary system for Antarctic chondrites listed in Table 1. These calculated values of $m$ and the four coercivity parameters for Model II are not substantially different from the corresponding values for Model I. Since the most probable value of $\beta$, which has been experimentally obtained as the average value of 17 measurements of 6 iron meteorites of less than 7.5 wt% in Ni content (*i.e.* a hexahedrite and 5 coarse octahedrites; NAGATA, 1987) and 11 metallic grains of a chondrite

*Table 2. Magnetic coercivity parameters of the binary system.*

| Chondrite | Model | $m$ (%) | $H_C^{(a)}$ (Oe) | $H_{RC}^{(a)}$ (Oe) | $H_C^{(b)}$ (Oe) | $H_{RC}^{(b)}$ (Oe) |
|---|---|---|---|---|---|---|
| Y-7301 | (I) | 1.7 | 2036 | 3053 | 7.5 | 31 |
| | (II) | 1.9 | 1542 | 2313 | 6 | 25 |
| Y-74647 | (I) | 2.5 | 1023 | 1534 | 5.5 | 22 |
| | (II) | 2.7 | 887 | 1330 | 4.5 | 18 |
| Y-74191 | (I) | 7.6 | 978 | 1467 | 7 | 28 |
| | (II) | 7.9 | 944 | 1416 | 5.5 | 22 |
| Y-74354 | (I) | 7.7 | 1925 | 2887 | 15.5 | 62 |
| | (II) | 7.9 | 1858 | 2787 | 12.5 | 50 |
| Y-74362 | (I) | 7.9 | 952 | 1428 | 9 | 35 |
| | (II) | 8.1 | 920 | 1381 | 7 | 28 |
| ALH-77260 | (I) | 7.2 | 846 | 1269 | 21 | 84 |
| | (II) | 7.5 | 817 | 1225 | 17 | 68 |
| ALH-769 (A-0) | (I) | 15.1 | 1462 | 2192 | 26 | 103 |
| (A-1) | (I) | 8.3 | 1967 | 2950 | 20.5 | 82 |
| (A-2) | (I) | 9.0 | 1784 | 2675 | 24 | 95 |
| (A-3) | (I) | 3.7 | 1566 | 2348 | 12 | 48 |
| ALH-769 (A-0) | (II) | 15.3 | 1440 | 2160 | 21 | 84 |
| (A-1) | (II) | 8.5 | 1905 | 2857 | 16.5 | 66 |
| (A-2) | (II) | 9.2 | 1734 | 2600 | 21 | 84 |
| (A-3) | (II) | 4.0 | 1432 | 2148 | 9.5 | 38 |

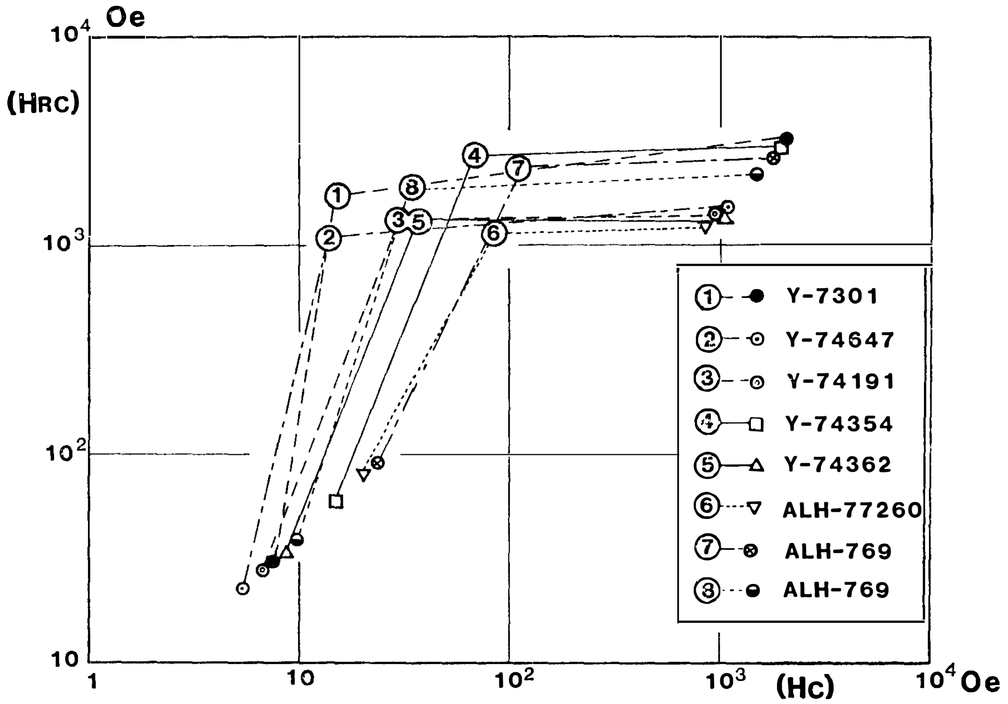

Fig. 2. $H_{RC}$ *vs.* $H_C$ *diagram for showing the decomposition of anomalously large values of* $H_{RC}/H_C$ *of Antarctic chondrites into a high coercivity component (a) and a low coercivity component (b) by assuming a magnetic binary model. (*$H_C$ *and* $H_{RC}$ *in logarithmic scale).*

(*i.e.* ALH-769; Funaki *et al.*, 1981) is given by $\beta=0.00310\pm0.00049$, $\beta=0.003$ will be assumed as the most probable value of $\beta$ in the following discussions.

Figure 2 is the plots of the original observed values of ($H_C$, $H_{RC}$) and the estimated values of ($H_C^{(a)}$, $H_{RC}^{(a)}$) and ($H_C^{(b)}$, $H_{RC}^{(b)}$) obtained with the aid of Model I for 7 Antarctic chondrites on a $H_{RC}$ *vs.* $H_C$ diagram in logarithmic scales (Nagata and Funaki, 1987). It is clearly shown in Fig. 2 that magnetic constituents in all these chondrites are composed of a high coercivity component (a) of $H_C^{(a)}\gtrsim10^3$ Oe and a low coercivity component (b) of $H_C^{(b)}\lesssim30$ Oe. It looks certain in the thermomagnetic characteristics of these chondrites that the largest parts of (b) component are occupied by multi-domain kamacite and probably a small portion may be multi-domain disordered taenite. It seems most likely, on the other hand, that (a)-component is either a metal phase having a highly uniaxial crystal anisotropy such as tetrataenite (*i.e.* $\gamma'$-FeNi) or very fine metallic grains having a large shape anisotropy (Nagata and Carleton, 1987).

As demonstrated in a previous paper (Nagata and Funaki, 1987), one of the necessary conditions for experimentally identifying the tetrataenite phase is an irreversible breakdown of tetrataenite phase ($\gamma'$-FeNi) to ordinary disordered taenite ($\gamma$-FeNi) by heating to an elevated temperature sufficiently higher than the $\gamma'\rightarrow\gamma$ transition temperature, 320°C. All the seven chondrites, shown in Table 1, have been confirmed to satisfy the necessary condition for evidence of tetrataenite phase (Nagata and Funaki, 1987). Figure 3 illustrates an $I_R/I_S$ *vs.* $H_{RC}$ diagram for Y-74354, -74362 and 2 samples (*i.e.* A-2 and A-3) of ALH-769, where observed values of $I_R/I_S$ and $H_{RC}$ of the chondrites before and after heating twice up to 850°C are plotted in logarithmic scale. $I_R/I_S$ values

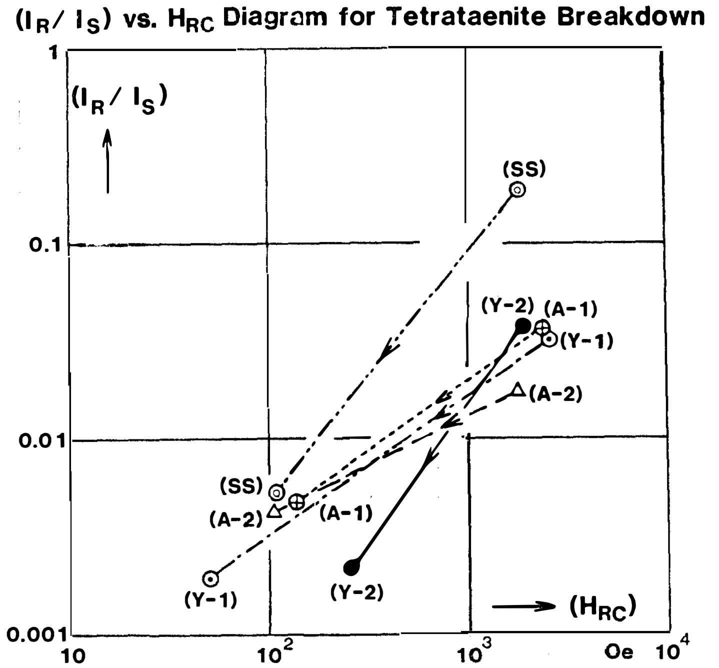

*Fig. 3. $I_R/I_S$ vs. $H_{RC}$ diagram for showing the breakdown of tetrataenite phase by heating. (SS): St. Séverin. (Y-1): Y-74354. (Y-2): Y-74362. (A-1): ALH-769 (A-1). (A-2): ALH-769 (A-2). ($I_R/I_S$ and $H_{RC}$ in logarithmic scale).*

of the four chondrite samples after the heating test range from 0.0020 to 0.0046, which are close to the allowable range of $\beta = I_R^{(b)}/I_S^{(b)}$ for the multi-domain low coercivity component. Similarly, their $H_C$ values after the heating test range from 5 to 10 Oe, which also are close to the allowable range of $H_C^{(b)}$.

$H_{RC}$ values of these chondrites also are much reduced from 1100–2620 Oe in the original pre-heating state to 50–255 Oe in the post-heating state. In Fig. 3, $I_R/I_S$ and $H_{RC}$ values of St. Séverin chondrite before and after the same heating test are plotted for reference. The presence of about 51% tetrataenite in metallic component of St. Séverin was directly detected and the $\gamma' \rightarrow \gamma$ breakdown phenomenon by the heating test has been studied in fair detail (NAGATA *et al.*, 1986). It will be almost certain, therefore, that the high coercive (a)-component in Y-74354, -74362 and ALH-769 chondrites is mostly tetrataenite phase. As for Y-7301, -74647, -74191 and ALH-77260 chondrites also, the same heating test leads to a conclusion that (a)-component in them can be identified to the tetrataenite phase, but not to the uniaxially shape-anisotropic single-domain phase of kamacite or ordinary taenite.

## 4. Magnetic Structure of Chondrules and Matrix of ALH-769 Chondrite

The magnetic hysteresis parameters of individual chondrules, metallic grains and matrix specimens of ALH-769 chondrite have been separately measured (NAGATA and FUNAKI, 1981; FUNAKI *et al.*, 1981). In Fig. 4, observed values of $I_R/I_S$ and $H_{RC}$ of 6

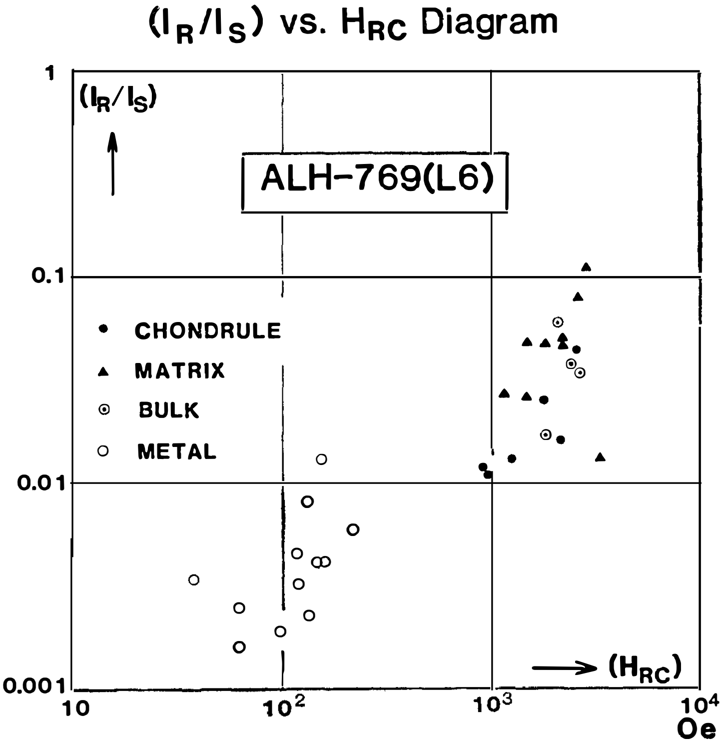

*Fig. 4.* *$I_R/I_S$ vs. $H_{RC}$ diagram of chondrule (N=6), matrix (N=9), metallic grains (N=12) and bulk samples (N=4) of ALH-769. ($I_R/I_S$ and $H_{RC}$ in logarithmic scale).*

chondrules, 12 metallic grains and 9 pieces of matrix separated from chondrules and visible metallic grains of ALH-769 chondrite are plotted, together with those of 4 pieces of bulk chondrite given in Table 1, on an $I_R/I_S$ *vs.* $H_{RC}$ diagram in logarithmic scale.

The mean values and the standard deviations of the means of $I_R/I_S$ and $H_C$ for the chondrules, the matrix pieces and the bulk specimens are

$$\overline{I_R/I_S}\ (\text{Chondrule}) = 0.0205 \pm 0.0059,\quad \overline{I_R/I_S}\ (\text{Matrix}) = 0.0504 \pm 0.0098,$$
$$\overline{I_R/I_S}\ (\text{Bulk}) = 0.0308 \pm 0.0093,\quad \overline{H_{RC}}\ (\text{Chondrule}) = 1636 \pm 385\ \text{Oe},$$
$$\overline{H_{RC}}\ (\text{Matrix}) = 1876 \pm 283\ \text{Oe and } \overline{H_{RC}}\ (\text{Bulk}) = 2287 \pm 370\ \text{Oe},$$

while those for the metallic grains are $\overline{I_R/I_S}$ (Metal) $=0.0046 \pm 0.0009$ and $\overline{H_{RC}}$ (Metal) $=120 \pm 44$ Oe. The two magnetic hysteresis parameters, $I_R/I_S$ and $H_{RC}$, of the groups of chondrules, matrix pieces and bulk specimens are close to one another in comparison with those of metallic grain group, as shown in Fig. 4. and numerically given with the mean values of $I_R/I_S$ and $H_{RC}$. On the contrary, $\overline{H_{RC}}$ (Metal) is approximately the same as $\overline{H_{RC}}^{(b)}=82 \pm 12$ Oe of the group of 4 bulk samples given in Table 2, and $\overline{I_R/I_S}$ (Metal) is of the same order of magnitude as $\beta=0.003$. In addition, $I_R/I_S$ and $H_{RC}$ values of (A-2) and (A-3) specimens after the heating test are $I_R/I_S=0.0046$ and $0.0043$ and $H_{RC}=130$ Oe and 110 Oe, respectively, which are roughly the same as $\overline{I_R/I_S}$ (Metal) and $\overline{H_{RC}}$ (Metal), respectively.

These experimental results strongly suggest that both chondrules and matrix excluding large grains (*i.e.* larger than 2 mg in weight in the present work) of metal in ALH-769 chondrite contain both a high coercivity metal (a) and a low coercivity metal (b), while the relatively large metallic grains contain the low coercivity (b) metal only, and further that the high coercivity (a) metal is mostly tetrataenite.

Hence, individual chondrules and matrix pieces are analyzed on the basis of the

*Table 3. Magnetic coercivity parameters of the binary system for chondrules and matrix of ALH-769.*

| Meteorite sample | | $m$ (%) | $H_C^{(a)}$ (Oe) | $H_{RC}^{(a)}$ (Oe) | $H_C^{(b)}$ (Oe) | $H_{RC}^{(b)}$ (Oe) |
|---|---|---|---|---|---|---|
| Chondrule | D-1 | 3.4 | 1855 | 2782 | 41 | 163 |
| | D-2 | 6.0 | 1336 | 2003 | 26 | 102 |
| | D-3 | 2.4 | 1164 | 1747 | 42 | 167 |
| | E-1 | 10.8 | 1882 | 2824 | 35 | 141 |
| | E-2 | 2.2 | 956 | 1434 | 21 | 83 |
| | F-2 | 2.4 | 889 | 1333 | 19 | 76 |
| Matrix | C-1 | 11.4 | 1280 | 1920 | 25 | 100 |
| | C-2 | 19.9 | 1795 | 2693 | 15 | 61 |
| | C-3 | 6.4 | 855 | 1283 | 12 | 47 |
| | C-4 | 2.7 | 3236 | 4855 | 62 | 246 |
| | C-5 | 26.4 | 1901 | 2852 | 4 | 15 |
| | C-6 | 13.0 | 1550 | 2326 | 29 | 117 |
| | C-7 | 11.8 | 1087 | 1630 | 26 | 102 |
| | C-8 | 6.1 | 1030 | 1695 | 10 | 41 |
| | C-9 | 11.1 | 1287 | 1931 | 22 | 89 |

binary system Model I, results being summarized in Table 3. The mean values and the standard deviations of the means of $m$, $H_C^{(a)}$ and $H_C^{(b)}$ for the group of 6 chondrules and that of 9 matrix pieces are

$$\bar{m}\,(\text{Chondrule}) = 4.6 \pm 1.4\%, \quad \bar{m}\,(\text{Matrix}) = 11.2 \pm 2.6\%,$$
$$\overline{H_C^{(a)}}\,(\text{Chondrule}) = 1347 \pm 177\ \text{Oe}, \quad \overline{H_C^{(a)}}\,(\text{Matrix}) = 1569 \pm 237\ \text{Oe},$$
$$\overline{H_C^{(b)}}\,(\text{Chondrule}) = 30.5 \pm 4.1\ \text{Oe}, \quad \overline{H_C^{(b)}}\,(\text{Matrix}) = 22.7 \pm 5.0\ \text{Oe},$$

respectively. Since $H_{RC}^{(a)}/H_C^{(a)} = 1.5$ and $H_{RC}^{(b)}/H_C^{(b)} = 4.0$ are assumed in the binary system model, the mean values and their standard deviations of $H_C^{(a)}$ and $H_C^{(b)}$ only will be concerned in the following statistical discussions without dealing with $H_{RC}^{(a)}$ and $H_{RC}^{(b)}$.

Since the magnetically analyzed samples of chondrule, matrix and bulk specimen are only 6, 9 and 4, respectively, in number, a statistical inference approach with the aid of Student's t-test may be required for comparing $m$, $H_C^{(a)}$ and $H_C^{(b)}$ values of each sample group with one another. The 95% confidence intervals for the inferred means, $\mu$, of population for $H_C^{(a)}$ (Chondrule), $H_C^{(b)}$ (Chondrule), $H_C^{(a)}$ (Matrix), $H_C^{(b)}$ (Matrix), $H_C^{(a)}$ (Bulk) and $H_C^{(b)}$ (Bulk) are illustrated in logarithmic scale in Fig. 5, where

$$892\ \text{Oe} < \mu\{H_C^{(a)}\ (\text{Chondrule})\} < 1802\ \text{Oe},$$
$$19.9\ \text{Oe} < \mu\{H_C^{(b)}\ (\text{Chondrule})\} < 41.1\ \text{Oe},$$
$$1008\ \text{Oe} < \mu\{H_C^{(a)}\ (\text{Matrix})\} < 2130\ \text{Oe},$$
$$11.0\ \text{Oe} < \mu\{H_C^{(b)}\ (\text{Matrix})\} < 34.5\ \text{Oe},$$

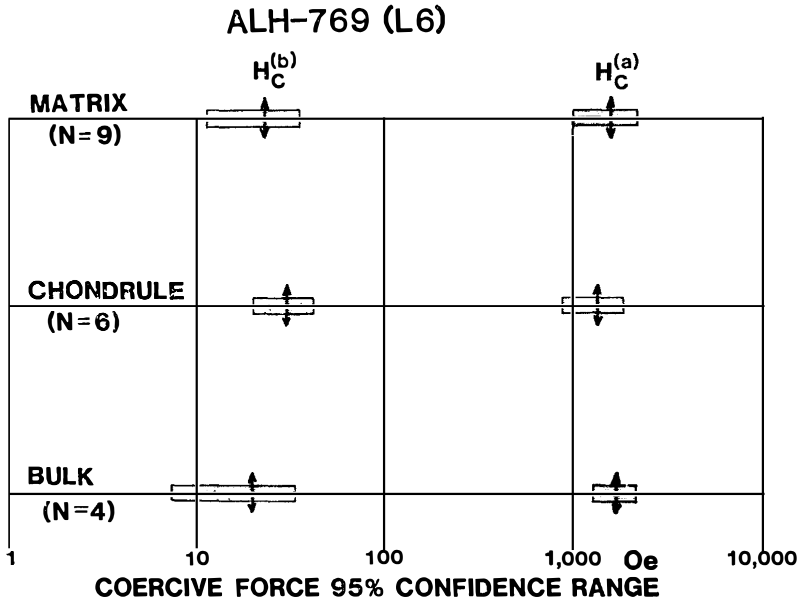

*Fig. 5. 95% confidence ranges for magnetic coercive forces of the high coercivity component ($H_C^{(a)}$) and the low coercivity component ($H_C^{(b)}$) of matrix, chondrule and bulk sample of ALH-769. Vertical arrows indicate the mean values of respective $H_C^{(a)}$ and $H_C^{(b)}$ values. ($H_C$ in logarithmic scale).*

$$1280\ \mathrm{Oe} < \mu\{H_C^{(a)}\ (\mathrm{Bulk})\} < 2180\ \mathrm{Oe},$$
$$7.7\ \mathrm{Oe} < \mu\{H_C^{(b)}\ (\mathrm{Bulk})\} < 32.9\ \mathrm{Oe}.$$

The present statistical problem is whether mutual differences among $\mu\{H_C^{(a)}$ (Chondrule)$\}$, $\mu\{H_C^{(a)}$ (Matrix)$\}$ and $\mu\{H_C^{(a)}$ (Bulk)$\}$ and among $\mu\{H_C^{(b)}$ (Chondrule)$\}$, $\mu\{H_C^{(b)}$ (Matrix)$\}$ and $\mu\{H_C^{(b)}$ (Bulk)$\}$ are significant at a certain given significance level. Results of the t-test of this problem lead to a conclusion that two hypotheses

(1) $\mu\{H_C^{(a)}\ (\mathrm{Chondrule})\} = \mu\{H_C^{(a)}\ (\mathrm{Matrix})\} = \mu\{H_C^{(a)}\ (\mathrm{Bulk})\}$, and

(2) $\mu\{H_C^{(b)}\ (\mathrm{Chondrule})\} = \mu\{H_C^{(b)}\ (\mathrm{Matrix})\} = \mu\{H_C^{(b)}\ (\mathrm{Bulk})\}$

cannot be rejected at 5% significance level, namely at 95% confidence level. It is most likely therefore that both $H_C^{(a)}$ (Chondrule) and $H_C^{(a)}$ (Matrix) are randomly selected samples from a same population of $H_C^{(a)}$, and likewise both $H_C^{(b)}$ (Chondrule) and $H_C^{(b)}$ (Matrix) are samples from a same population of $H_C^{(b)}$, at the level of 95% confidence in terms of statistics.

A significant conclusion which may be derived from the result of analysis will be that the magnetically coercive tetrataenite phase is maintained in the chondrules approximately in the same condition as in the matrix. The transition temperature between tetrataenite and disordered ordinary taenite is 320°C, and the superlattice structure of tetrataenite is almost completely borken down to be irreversibly transformed to disordered taenite structure by heating up to 800°C only for several minutes. On the other hand, the tetrataenite formation in the cooling process of a disordered taenite crystal of 50Fe50Ni (in atomic ratio) in composition has not yet been experimentally realized even with extremely slow cooling rate below 320°C available in the present human laboratory. The ordering of tetrataenite superlattice structure can be achieved with irradiation by an appropriate flux of neutron (NÉEL *et al.,* 1964) or electron (*e.g.* REUTER *et al.,* 1985). It is generally believed, however, that the tetrataenite structure could be formed by extraordinarily slow cooling of 50Fe50Ni disordered taenite below 320°C.

Therefore, the observed existence of tetrataenite in chondrules as well as in matrix of ALH-769 chondrite suggests that the chondrules were cooled down very slowly, together with the matrix, from a temperature sufficiently higher than 320°C to result in a precipitation of 50Fe50Ni metal phase from Fe-Ni melt, and then further cooled down extraordinarily slowly to form the tetrataenite structure in the last stage of their thermal history. Such a slow cooling process as mentioned above could take place only within the deep interior of a chondrite-mother planetesimal body of a sufficiently large size. There would be various possible models for consistently explaining the chondrule formation process including a number of observed petrographical and mineralogical key characteristics of silicate minerals of chondrules (*e.g.* WASSON, 1974; DODD, 1981; NAGAHARA, 1981) and also evidence of the presence of tetrataenite in chondrules in ordinary chondrites. In the case of ALH-769 chondrite at least, however, it is an indispensable condition for the final process of chondrule formation that the chondrules were cooled down extraordinarily slowly through 320°C, most probably together with the matrix, so that the superlattice structure of tetrataenite was formed by a transformation from disordered taenite of 50Fe50Ni in both chondrules and matrix. This inference is based on the observed fact that Ni-rich iron meteorites can consist of various complicated combinations of disordered ordinary taenite, tetrataenite and martensitic $\alpha_2$-phase in addition to kamacite in their structure, probably owing to differences in their thermal histories, as demonstrated by NAGATA *et al.* (1987) for example.

Further discussions on possible formation processes of tetrataenite phase in ALH-769 chondrules in conjunction with those of the other chondrites as a whole would be premature at the present stage of experimental results. The following additional notes are concerned simply with observed similarities and discrepancies among the fine metallic particles in chondrules, matrix, and relatively large metallic grains in ALH-769 chondrite for the purpose of further consideration of the problem in the future.

( i ) Content ($m$) of tetrataenite in metal

The mean values of tetrataenite content ($m$) in metals in chondrules and matrix are given by $m(\text{Matrix}) = 11.22 \pm 2.60\%$ and $m(\text{Chondrule}) = 4.55 \pm 1.38\%$, where numeral figure after ± is the standard deviation of the mean. Although $m$(Matrix) is about double $m$(Chondrite), a working hypothesis that $\mu\{m(\text{Chondrite})\} = \mu\{m(\text{Matrix})\}$ cannot be rejected at 5% significance level in the statistical inference test.

(ii) Content ($p$) of Fe-Ni metal in chondrules and matrix

Content of Fe-Ni metal in ordinary chondrites can be approximately represented by their $I_S$ values. Taking into account coexistence of Ni-rich taenite phase in metal, $I_S \simeq 200$ emu/g can be taken as the average value of chondritic metal itself. The mean $I_S$ values of 9 matrix pieces, 6 chondrules and 4 bulk specimens are given, respectively, by $\overline{I_S}$ (Matrix) $= 9.09 \pm 1.37$ emu/g, $\overline{I_S}$ (Chondrule) $= 2.24 \pm 1.00$ emu/g and $\overline{I_S}$ (Bulk) $= 9.15 \pm 0.83$ emu/g. $\overline{I_S}$ (Matrix) is nearly the same as $\overline{I_S}$ (Bulk), but a working hypothesis that $\mu\{I_S(\text{Chondrite})\} = \mu\{I_S(\text{Matrix})\}$ must be rejected at 5% significance level. The average content of metal in chondrules is about one fourth of that in matrix.

## 5. Concluding Remarks

In the foregoing sections, it is demonstrated with Antarctic chondrites that the present magnetic binary system model is practically applicable on interpreting the magnetic structure of metallic components in stony meteorites, particularly ordinary chondrites which have anomalously large values of $H_{RC}/H_C$. The concept of a binary system is experimentally introduced by taking into consideration remanence coercive force, $H_{RC}$, in addition to ordinary coercive force, $H_C$. The observed magnetic hysteresis parameters for the present binary system model are $I_S$, $I_R$, $H_C$ and $H_{RC}$ for each sample. From these four magnetic hysteresis parameters, four unknown parameters representing the binary system structure can be determined with the aid of the present binary system model. The four unknown parameters of the binary system to be determined are (i) content ($p$) of the total ferromagnetic constituent in a rock sample, (ii) content ($m$) of the high coercivity component (a) in the ferromagnetic constituent, (iii) $H_C^{(a)}$ and (iv) $H_C^{(b)}$. $H_{RC}^{(a)}$ and $H_{RC}^{(b)}$ of the binary system are related by assumed coefficients, A and B, with $H_C^{(a)}$ and $H_C^{(b)}$ respectively.

In some meteorites, it appears very likely that their ferromagnetic constituents consist of three or more components. For example, several metallic particles in ALH-769 chondrite, $I_R/I_S$ values of which are larger than 0.08, consist of 2–3% of single-domain taenite phase of $H_C=130$–$160$ Oe and the major component of kamacite of $H_C=7$–$8$ Oe, so that total ferromagnetic phases in ALH-769 as a whole are multi-domain kamacite, tetrataenite and single-domain taenite. It is obvious that a package of four observed magnetic hysteresis parameters is not sufficient to exactly analyze the structure of such a magnetic ternary system.

Nevertheless, it seems likely that the present binary system model can be applied on approximately analyzing the magnetic structure of ordinary chondrites in many cases as shown for example in Tables 1 and 2. This applicability of the binary system model may probably be due to a fact in nature that the dominant ferromagnetic components are only two, (a) high coercivity component having a strong magnetic uniaxial anisotropy and (b) low coercivity component having multi-domain structure, in most ordinary chondrites. Since presence of an extremely high coercivity component is fundamentally significant in meteoritic paleomagnetism, it would be recommended first that $H_{RC}$ is measured whenever magnetic hysteresis characteristics of stony meteorite are experimentally examined, and secondly that a binary system model analysis is carried out, if $I_R/I_S$ is considerably larger than 0.003 and $H_{RC}/H_C$ is much larger than 5. If $I_R/I_S$ is nearly 0.1 or larger and both $H_{RC}$ and $H_C$ are anomalously large, say, $H_{RC}\gtrsim 1000$ Oe and $H_C\gtrsim 500$ Oe, for a stony meteorite, however, the observed magnetic characteristics strongly suggest that the metallic constituent of the meteorite contains several tens of percent of tetrataenite phase, even though $H_{RC}/H_C$ is smaller than 5 (*e.g.* NAGATA *et al.*, 1986; NAGATA and FUNAKI, 1987). For example, the magnetic hysteresis parameters of a St. Séverin chondrite sample is given by $I_S=2.80$ emu/g, $I_R=0.50$ emu/g, $H_C=520$ Oe and $H_{RC}=1840$ Oe, so that $I_R/I_S=0.179$ and $H_{RC}/H_C=3.54$. Results of a binary system model analysis of these observed data are expressed by $m=0.403$, $H_C^{(a)}=1240$ Oe, $H_{RC}^{(a)}=1859$ Oe, $H_C^{(b)}=49$ Oe and $H_{RC}^{(b)}=196$ Oe, while a Mössbauer spectral analysis of another sample of the same chondrite has given $m=0.51$ (NAGATA *et al.*, 1986). It is self-evident that a ferromagnetic material having a large value of $H_C$ has a large value of $H_{RC}$ too.

As generally discussed in a separate paper (NAGATA and CARLETON, 1987), $\zeta^*/\zeta$ takes its maximum value around $\xi\equiv mY/\{mY+(1-m)\}=3/4$ for large values of $\eta$ and $\eta^*$, *i.e.* $\eta^*>10$. Since a reasonable value of $Y$ assumes $Y=127$ in Model I for ordinary chondrites, the maximum value of $\zeta^*/\zeta$ of ordinary chondrites takes place around $m=0.023$. It is actually seen in Tables 1 and 2 that $H_{RC}/H_C$ larger than 10 are observed in the case of $m<0.1$, and the extremely large values of $H_{RC}/H_C$ of Y-7301 and -74647 chondrites correspond to $m$ values around $m=0.02$.

Since it seems very likely that Fe-Ni metallic grains in ordinary chondrites often consist of a small amount of tetrataenite and the major phases of kamacite and disordered taenite, the magnetic binary system analysis of ordinary chondrites could be recommended as one of fruitful methods of their magnetic analysis.

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## References

DODD, R. T. (1981): Meteorites; A Petrologic-Chemical Synthesis. Cambridge, Cambridge Univ. Press, 368 P.

FUNAKI, M., NAGATA, T. and MOMOSE, K. (1981): Natural remanent magnetizations of chondrules, metallic grains and matrix of Antarctic chondrite, ALH-769. Mem. Natl Inst. Polar Res., Spec. Issue, **20**, 300–315.

NAGAHARA, H. (1981): Evidence for secondary origin of chondrules. Nature, **292**, 135–136.

NAGATA, T. (1987): Nankyoku inseki no jiki bussei (Magnetic properties of Antarctic meteorites). Nankyoku no Kagaku, 6. Nankyoku Inseki (Science in Antarctica, 6. Antarctic Meteorites), ed. by Kokuritsu Kyokuchi Kenkyûjo. Tokyo, Kokon Shoin, 308–337.

NAGATA, T. and CARLETON, B. J. (1987): Magnetic remanence coercivity of rocks. J. Geomagn. Geoelectr., **39**, 447–461.

NAGATA, T. and FUNAKI, M. (1981): The composition of natural remanent magnetization of an Antarctic chondrite, ALH-76009 (L6). Proc. Lunar Planet Sci. Conf., 12B, 1229–1241.

NAGATA, T. and FUNAKI, M. (1982): Magnetic properties of tetrataenite-rich stony meteorites. Mem. Natl Inst. Polar Res., Spec. Issue, **25**, 222–250.

NAGATA, T. and FUNIAKI, M. (1987): Tetrataenite phase in Antarctic meteorites. Mem. Natl Inst. Polar Res., Spec. Issue, **46**, 245–262.

NAGATA, T. and SUGIURA, N. (1976): Magnetic characteristics of some Yamato meteorites. Mem. Natl Inst. Polar Res., Ser. C (Earth Sci.), **10**, 30–58.

NAGATA, T. FUNAKI, M. and DANON, J.A. (1986): Magnetic properties of tetrataenite-rich meteorites II. Mem. Natl Inst. Polar Res., Spec. Issue, **41**, 364–381.

NAGATA, T., DANON, J. A. and FUNAKI, M. (1987): Magnetic properties of Ni-rich iron meteorites. Mem. Natl Inst. Polar Res., Spec. Issue, **46**, 263–282.

NÉEL, L., PAULEVE, J., PAUTHENET, R., LAUGIER, J. and DAUTREPPE, D. (1964): Magnetic properties of an iron-nickel single crystal ordered by neutron bombardment. J. Appl. Phys., **35**, 873–876.

REUTER, K. B., WILLIAMS, D. B. and GOLDSTEIN, J. I. (1985): A contribution to the low temperature Fe-Ni phase diagram. Meteoritics, **20**, 742–743.

WASSON, J.T. (1974): Meteorites. Berlin, Springer, 316 p.

WOHLFARTH, E. P. (1958): Relation between different modes of acquisition of the remanent magnetization of ferromagnetic particles. J. Appl. Phys., **29**, 595–596.

WOHLFARTH, E. P. (1963): Remanent magnetization materials. Magnetism, Vol. III, ed. by G. E. RADO and H. SUHL. New York, Academic Press, 351–393.

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