PIEZOMAGNETIZATION OF METEORITES

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***Abstract*:** The piezo-remanent magnetization (PRM) of Mt. Baldr b (H5–6) and ALH-769 (L6) chondrites and Yamato-74013 diogenite is experimentally demonstrated. $J_r^{//}(H_+P_+P_0H_0)$ of these stony meteorites is approximately proportional to an applied magnetic field, H, when P is kept constant. There is a possibility that the natural remanent magnetization of the two chondrites is due to an acquisition of PRM in a weak magnetic field.

Dependence of magnetic susceptibility of a stony meteorite upon applied uniaxial compression and the magnetic susceptibility anisotropy of stony meteorites also are experimentally examined.

1. Introduction

Effects of mechanical stresses on the magnetization processes of terrestrial rocks have been studied in fair detail as summarized by NAGATA (1970a). One of the stress effects on rock magnetization is the shock remanent magnetization (SRM), which is produced by an application of compressional shock on a rock specimen in the presence of a magnetic field (NAGATA, 1971). The mechanism of production of SRM is essentially the same as that of piezo-remanent magnetization (PRM) which is produced by static uniaxial compression of the same rock specimen in the presence of a magnetic field.

It is generally believed that meteorites have been impacted in their past history. If there is a magnetic field in extraterrestrial space where a meteorite piece was impacted, the meteorite should have acquired SRM. In the present work, the basic characteristics of PRM of selected meteorite samples are experimentally studied. Selected meteorite samples are Mt. Baldr b (H5–6), ALH-769 (L6) and Yamato-74013 (diogenite) with three different levels of metallic iron content. As summarized in Table 1, the saturation magnetization (I_s) is 27.4, 8.35 and 0.17 emu/g for Mt. Baldr b, ALH-769 and Yamato-74013 respectively, which indicates that the metallic iron content in these meteorites is about 13.7, 4.18 and 0.085 wt% respectively. As indicated by their values of coercive force (H_C) and the ratio I_R/I_s, given in Table 1, ALH-769 L6 chondrite is magnetically much more coercive than Mt. Baldr b (H5–6) chondrite and Yamato-74013 diogenite.

Table 1. Basic magnetic properties of natural remanent magnetization of meteorites examined in the present work.

Magnetic parameter	Mt. Baldr b (H5–6)	ALH-769 (L6)	Yamato-74013 (Diogenite)	Unit
I_s	27.4	8.35	0.17	emu/g
I_R	0.14	0.52	0.0012	〃
H_C	12	160	10	Oe
H_{RC}	240	2,100	20	〃
$I_n(0)$	1.12×10^{-4}	1.06×10^{-4}	3.46×10^{-5}	emu/g
$I_n(40)$	0.051×10^{-4}	0.25×10^{-4}	3.22×10^{-5}	〃
$I_n(80)$	0.018×10^{-4}	0.015×10^{-4}	3.00×10^{-5}	〃
$I_n(200)$	0.001×10^{-4}	0.005×10^{-4}	1.44×10^{-5}	〃

I_s=Saturation magnetization. I_R=Saturated isothermal remanent magnetization. H_C=Coercive force. H_{RC}=Remanence coercive force. $I_n(0)$=Natural remanent magnetization (NRM). $I_n(40)$= NRM after AF-demagnetization to 40 Oe peak. $I_n(80)$=NRM after AF-demagnetization to 80 Oe peak. $I_n(200)$=NRM after AF-demagnetization to 200 Oe peak.

In Table 1, the original intensity ($I_n(0)$) of natural remanent magnetization (NRM) and the residual NRM intensity after AF-demagnetizing up to 40 Oe peak ($I_n(40)$), to 80 Oe peak ($I_n(80)$) and to 200 Oe peak ($I_n(200)$) are also given for these three meteorites. As suggested by the ratios $I_n(40)/I_n(0)$, $I_n(80)/I_n(0)$ and $I_n(200)/I_n(0)$, NRM's of Mt. Baldr b and ALH-769 are almost completely AF-demagnetized by an alternating magnetic field of 10^2 Oe peak, while the NRM of Yamato-74013 is relatively stable for the AF-demagnetization test.

2. Piezo-remanent Magnetization

As generally discussed by NAGATA and CARLETON (1969), piezo-remanent magnetization can be classified into six categories as expressed by $J_r(H_+H_0P_+P_0)$, $J_r(H_+P_+H_0P_0)$, $J_r(H_+P_+P_0H_0)$, $J_r(P_+P_0H_+H_0)$, $J_r(P_+H_+P_0H_0)$ and $J_r(P_+H_+H_0P_0)$, where H_+ indicates an application of a magnetic field H, and H_0 a release of H, and similarly P_+ an application of a uniaxial compression of pressure P, and P_0 a release of P, and the order from left to right in parentheses indicates the order of the sequence of operations H_+, H_0, P_+ and P_0. In the same terminology, an ordinary isothermal remanent magnetization (IRM) acquired in a magnetic field H is expressed by $J_r(H_+H_0)$. Among the six categories of PRM, $J_r(H_+H_0P_+P_0)$ means the pressure demagnetization of IRM, while $J_r(P_+P_0H_+H_0)$ means an initial compression effect on IRM, and therefore $J_r(H_+H_0P_+P_0)$ and $J_r(P_+P_0H_+H_0)$ are to be eliminated from the ordinary sense of PRM.

The four other categories of PRM could be considered as piezo-remanent magnetization. Relative relations among the four categories of PRM have been examined experimentally and theoretically in fair detail for the case of terrestrial igneous rocks (NAGATA, 1966; NAGATA and CARLETON, 1969). Among the four categoreis of PRM, $J_r(H_+P_+P_0H_0)$ is the most sensitive to the effect of an application and a release of P on the remanent magnetization, and is most likely to take place in nature. In the case of the meteorite, for example, $J_r(H_+P_+P_0H_0)$ corresponds to natural remanent magnetization acquired by an impact of P in compression magnitude in the presence of an ambient magnetic field H. In the present work, therefore, characteristics of $J_r(H_+P_+P_0 H_0)$ of meteorites will be experimentally examined.

Generally, PRM characteristics must be examined at least for two cases, *i.e.* a case in which the axis of P is parallel to the direction of H ($J_r^{/\!/}$) and the case in which the axis of P is parpendicular to the direction of H($J_r^{\perp}$). Since the effect of P is larger in $J_r^{/\!/}$ than in $J_r^{\perp}$, and the characteristics of $J_r^{\perp}$ of a sample can be theoretically derived from those of $J_r^{/\!/}$, $J_r^{/\!/}(H_+P_+P_0H_0)$ only will be dealt with in the present work.

Test samples of meteorite are of a cubic shape, and compression P is given on two parallel square planes of a cubic sample by a compressor anvil made of phosphor-bronze which is set at the center of a three-axis Helmholtz coil system. The remanent

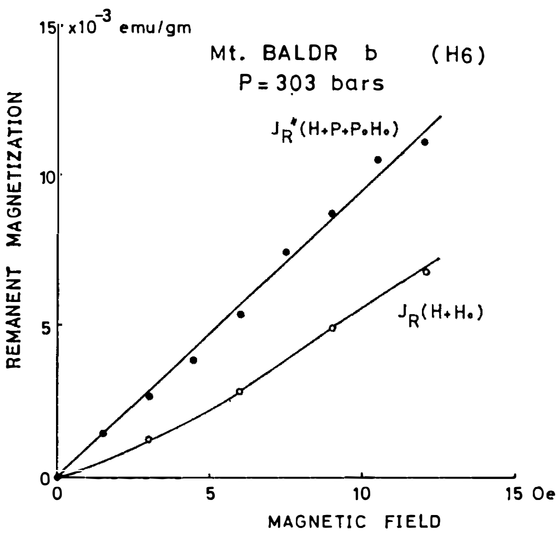

Fig. 1. PRM, $J_r^{/\!/}(H_+P_+P_0H_0)$ vs. H for Mt. Baldr b (H5–6) chondrite.

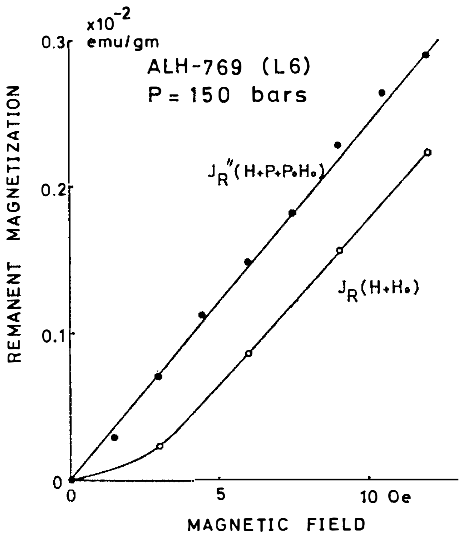

Fig. 2. PRM, $J_r^{/\!/}(H_+P_+P_0H_0)$ vs. H for ALH-769 (L6) chondrite.

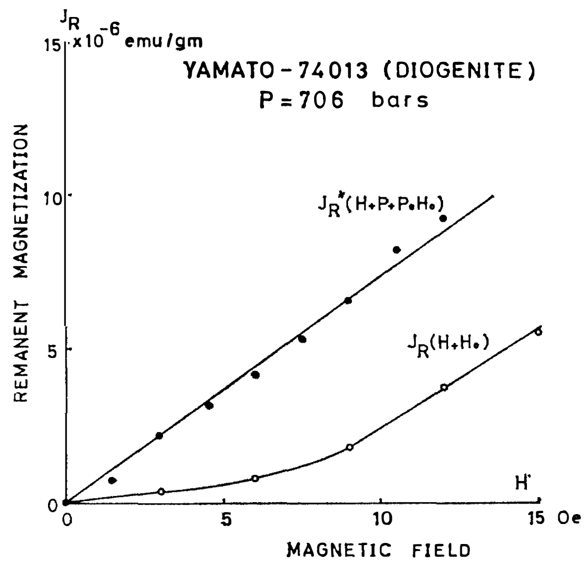

Fig. 3. PRM, $J_r^{/\!/}(H_+P_+P_0H_0)$ vs. H for Yamato-74013 diogenite.

Table 2. Characteristic parameters of PRM of meteorites.

Parameters	Mt. Baldr b (H5–6)	ALH-769 (L6)	Yamato-74013 (Diogenite)	Unit
C	3.1×10^{-6}	1.6×10^{-6}	1.1×10^{-9}	emu/g/Oe bar
b	8.6×10^{-5}	2.45×10^{-5}	2.4×10^{-8}	emu/g/Oe^2
C/b	3.6×10^{-2}	6.4×10^{-2}	4.6×10^{-2}	Oe/bar
H^* for $P=10$ kbars	3.6×10^{-3}	6.6×10^{-3}	3.15	Oe

magnetization acquired by Yamato-74013 was measured by a SQUID magnetometer while that of the two chondrites was measured by a spinner magnetometer.

Figures 1, 2 and 3 show the dependence on H of $J_r^{/\!/}(H_+P_+P_0H_0)$ acquired at a constant value of P and the dependence on H of $J_r(H_+H_0)$ for comparison for Mt. Baldr b, ALH-769 and Yamato-74013 respectively.

In the case of the meteorites also, $J_r^{/\!/}(H_+P_+P_0H_0)$ is approximately proportional to H when P is constant, whereas $J_r(H_+H_0)$ is approximately proportional to H^2 for small values of H. It can be seen that $J_r^{/\!/}(H_+P_+P_0H_0)$ is approximately proportional to P also when H is small and P is relatively large. We can express thus

$$J_r^{/\!/}(H_+P_+P_0H_0)\simeq CHP, \tag{1}$$

$$J_r(H_+H_0)=bH^2. \tag{2}$$

In Table 2, the observed values of C, b and the ratio C/b for the three meteorites are summarized. If we assume that NRM of these meteorites is attributable to $J_r^{/\!/}(H_+P_+P_0H_0)$ acquired by an impact of $P=10$ kbars in the presence of an ambient magnetic field H^*, the estimated magnitude of H^* is 0.0036 Oe and 0.0066 Oe respectively for Mt. Baldr b H5–6 chondrite and ALH-769 L6 chondrite, while H^* is estimated to be 3.15 Oe for the Yamato-74013 diogenite, as given in Table 2. If P assumes a larger value, H^* becomes smaller. It seems possible that the NRM of Mt. Baldr b and ALH-769 was acquired as PRM caused by a severe impact in a weak magnetic field H^*, because the AF-demagnetization curve characteristics of their NRM are not much different from those of their PRM. However, it seems very difficult to assume that the NRM of Yamato-74013 is due to acquisition of PRM, because the AF-demagnetization curve of its NRM is much more gradual than that of its PRM, in addition to an unreasonably large value of $H^*=3.15$ Oe.

For a sufficiently small value of H and a sufficiently large value of P, namely, when $H\ll3|\bar\lambda|P/\sqrt{2}J_s$, $J_r^{/\!/}(H_+P_+P_0H_0)$ is theoretically expressed (NAGATA and CARLETON, 1969) by

$$J_r^{/\!/}(H_+P_+P_0H_0)=\frac{48\,b}{5\sqrt{2}\,\pi}\,\frac{|\bar\lambda|}{J_s}HP, \tag{3}$$

where $\bar\lambda$ and J_s denote respectively the isotropic (average) magnetostriction coefficient and the spontaneous magnetization. Hence the ratio C/b is thoretically given by

$$C/b=\frac{48}{5\sqrt{2}\,\pi}\,|\bar\lambda|/J_s. \tag{4}$$

In Table 2, the observed values of C/b are about $(4\text{–}6)\times 10^{-2}$ Oe/kg/cm^2, or $(4\text{–}6)\times 10^{-8}$ cgs emu. Since J_s of Fe-Ni metals (kamacite plus plessite) in the three meteorites is $(1.3\text{–}1.7)\times 10^3$ emu/cm^3, $|\bar{\lambda}|$ is evaluated to be about $(2\text{–}5)\times 10^{-5}$.

3. Effect of Uniaxial Compression on Magnetic Susceptibility

Measurements of the effect of mechanical stress on the magnetic susceptibility (χ) of meteorites are somewhat difficult compared with similar measurements on terrestrial rocks, because the expected effect of mechanical stress on χ of meteorites is considerably smaller than that on χ of terrestrial rocks, as theoretically discussed later.

The magnetic susceptibility as a function of an applied uniaxial compression (P) of Mt. Baldr b H5–6 chondrite was measured by an alternating field susceptibility bridge, where the axis of compression is parallel to the direction of magnetic field ($\tilde{H}=0.2$ Oe peak). The observed values of susceptibility ($\chi^{\prime\prime}(P)$) under uniaxial compression P are shown in Fig. 4, where $\chi^{\prime\prime}(P)$ is normalized by the initial susceptibility (χ_0) without the effect of P. $\chi^{\prime\prime}(P)$ can be approximately expressed as

$$\chi^{\prime\prime}(P)=\frac{\chi_0}{1+\beta P}, \tag{5}$$

where $\chi_0=1.76\times 10^{-2}$ emu/g/Oe and $\beta=6\times 10^{-5}$ cm^2/kg.

It has been demonstrated (NAGATA, 1970a, b) that the dependence of $\chi^{\prime\prime}(P)$ of terrestrial rocks can be generally expressed by eq. (5). On the other hand, $\chi^{\prime\prime}(P)$ may be theoretically expressed (NAGATA, 1970b) by

$$\chi^{\prime\prime}(P)=\frac{\chi_0}{1+\beta P}, \tag{5}$$

and

$$\beta=\frac{3\bar{\lambda}}{NJ_s^2+4K/3\pi}, \tag{6}$$

where N and K denote respectively the average demagnetizing factor of ferromagnetic grains in a non-magnetic matrix and the magnetic anisotropy energy of ferromagnetic

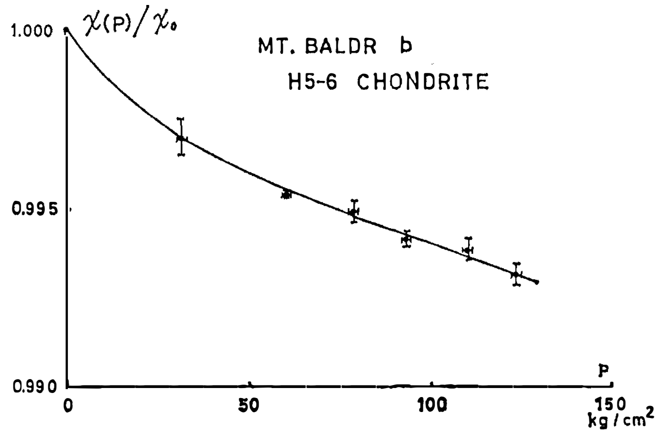

Fig. 4. Magnetic susceptibility $\chi^{\prime\prime}(P)$ vs. uniaxial compression (P) for Mt. Baldr b chondrite.

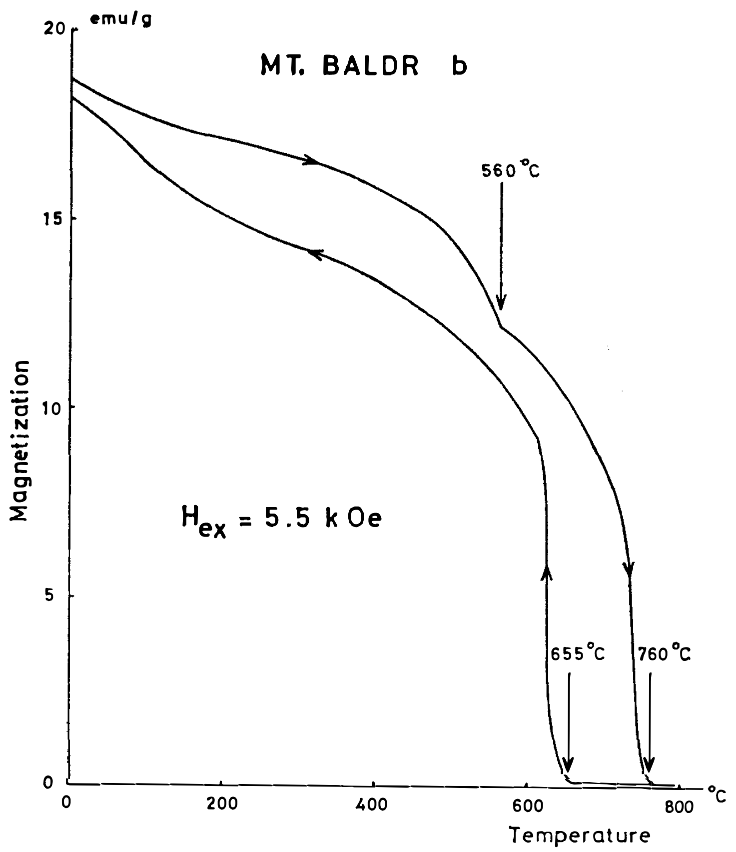

Fig. 5. Thermomagnetic curves for Mt. Baldr b chondrite.

grains. If the ferromagnetic grains are pure magnetite as in many terrestrial rocks, $J_s=480$ emu/cm^3, $K=-1.2\times10^5$ erg/cm^3. $\bar{\lambda}=41\times10^{-6}$ and $N=3.4$, whence $|4K/3\pi|\ll NJ_s^2$ and $\beta\simeq1.6\times10^{-10}$ cm^2/erg$=1.6\times10^{-4}$ cm^2/kg. The β-value thus theoretically estimated is in approximate agreement with observed data for most terrestrial rocks.

If the ferromagnetic constituent is pure iron, $J_s=1.7\times10^3$ emu/cm^3, $K=4.6\times10^5$ erg/cm^3 and $\bar{\lambda}=-4.4\times10^{-6}$. Putting $N\simeq3.4$, we get $|4K/3\pi|\ll NJ_s^2$ and $\beta=-1.3\times10^{-6}$ cm^2/kg. The result of this theoretical estimate suggests that $\chi''(P)/\chi_0>1$ and $\partial[\chi''(P)/\chi_0]/\partial P$ is positive and very small for rock samples containing only pure iron grains.

In the case of Mt. Baldr b, however, β is about $+6\times10^{-5}$ cm^2/kg, which means that $\bar{\lambda}$ is positive. Therefore, the metallic component in Mt. Baldr b is considerably different from pure iron in its chemical composition.

Thermomagnetic curves of Mt. Baldr b are shown in Fig. 5, which indicates that the Fe-Ni metal in this chondrite consists of kamacite phase (α-phase) of 5.2 wt% Ni which gives $\Theta^*_{\alpha\to\gamma}=760°$C and $\Theta^*_{\gamma\to\alpha}=655°$C, plessite phase (($\alpha+\gamma$)-phase) whose transformation temperature in the heating process is 560°C and a small amount of taenite phase (γ-phase) of about 35 wt% Ni. Intensities of saturation magnetization (I_s) of α-, ($\alpha+\gamma$)- and γ-phase component and their total being denoted by $I_s(\alpha)$, $I_s(\alpha+\gamma)$, $I_s(\gamma)$ and I_s respectively, the observed thermomagnetic curves indicate that $I_s(\alpha)/I_s=0.86$, $I_s(\alpha+\gamma)/I_s=0.11$ and $I_s(\gamma)/I_s=0.03$ in the initial state. The magnetostriction coefficients, λ_{100} and λ_{111}, of α- and γ-phases of Fe-Ni alloy of for 1–38 wt% in Ni-content have not yet been determined, so that $\bar{\lambda}=(2/5)\lambda_{100}+(3/5)\lambda_{111}$ for those metallic phases in Mt. Baldr b is not known.

If eqs. (5) and (6) are simply applied for the case of Mt. Baldr b and $J_s=1.3\times10^3$ emu/cm^3, $K=10^5$ erg/cm^3 and $N=3.4$ are assumed, $\bar{\lambda}$ is evaluated from the β-value to be about $+1\times10^{-4}$. On the other hand, the $\bar{\lambda}$ value estimated from PRM data of this chondrite is about $+2.2\times10^{-5}$. As NAGATA's theory (1970b) of $\chi''(P)$ is based on the assumption that all ferromagnetic grains have the single-domain structure, the theory may not be quantitatively applied to Mt. Baldr b, in which the majority of metallic grains are large enough to be multi-domain. On the contrary, the NAGATA-CARLETON theory of $J_r''(H_+P_+P_0H_0)$ deals with an assemblage of multi-domain ferromagnetic grains in a non-magnetic matrix so that the $\bar{\lambda}$-value derived from C/b will be more reliable.

4. Magnetic Susceptibility Anisotropy

It has been generally recognized that most stony meteorites have a large anisotropy in their magnetic susceptibility. Such a magnetic susceptibility anisotropy of meteorites may be mostly due to plastic deformation caused by impact or by static stress in the interior of their mother planet or planetesimal. Figure 6 illustrates an example of observed curves of anisotropic magnetic susceptibility dependent on angle φ for Mt. Baldr b, where

$$\left.\begin{aligned}\chi(\xi,\eta)&=\frac{1}{2}(k_{\xi\xi}+k_{\eta\eta})+\frac{1}{2}(k_{\xi\xi}-k_{\eta\eta})\cos 2\varphi+k_{\xi\eta}\sin 2\varphi,\\ \chi(\eta,\zeta)&=\frac{1}{2}(k_{\eta\eta}+k_{\zeta\zeta})+\frac{1}{2}(k_{\eta\eta}-k_{\zeta\zeta})\cos 2\varphi+k_{\eta\zeta}\sin 2\varphi,\\ \chi(\zeta,\xi)&=\frac{1}{2}(k_{\zeta\zeta}+k_{\xi\xi})+\frac{1}{2}(k_{\zeta\zeta}-k_{\xi\xi})\cos 2\varphi+k_{\zeta\xi}\sin 2\varphi,\end{aligned}\right\}\quad(7)$$

for a symmetric tensor of anisotropic susceptibility,

$$(\chi)=\begin{pmatrix}k_{\xi\xi} & k_{\xi\eta} & k_{\xi\zeta}\\ k_{\xi\eta} & k_{\eta\eta} & k_{\eta\zeta}\\ k_{\xi\zeta} & k_{\eta\zeta} & k_{\zeta\zeta}\end{pmatrix}. \quad(8)$$

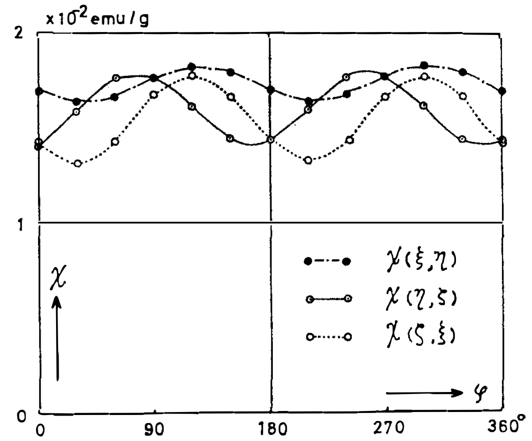

Fig. 6. Magnetic susceptibility anisotropy curves for Mt. Baldr b chondrite.
$\chi(\xi,\eta)$: Cyclic change of χ around ζ-axis.
$\chi(\eta,\zeta)$: Cyclic change of χ around ξ-axis.
$\chi(\zeta,\xi)$: Cyclic change of χ around η-axis.

Table 3. Anisotropic magnetic susceptibility of stony meteorites.

Meteorites	χ_{max} (emu/g/Oe)	χ_{int} (emu/g/Oe)	χ_{min} (emu/g/Oe)	$\frac{\chi_{max}-\chi_{min}}{\chi_{min}}$
Mt. Baldr b (H5-6)	1.82×10^{-2}	1.77×10^{-2}	1.31×10^{-2}	39%
Nuevo Mercurio (H5)	2.01×10^{-2}	1.76×10^{-2}	1.64×10^{-2}	23%
ALH-769 (L6)	5.51×10^{-3}	5.36×10^{-3}	4.52×10^{-3}	22%
Allende (C3)	4.88×10^{-4}	4.46×10^{-4}	4.01×10^{-4}	22%

An analysis of these observed curves gives rise to ratios among the maximum, intermediate and minimum values of anisotropic susceptibility tensor as $\chi_{max}: \chi_{int}: \chi_{min}=1.82\times10^{-2}: 1.77\times10^{-2}: 1.31\times10^{-2}$ emu/g/Oe. In Table 3, χ_{max}, χ_{int} and χ_{min} of three other stony meteorites are summarized together with those of Mt. Baldr b. As indicated by $(\chi_{max}-\chi_{min})/\chi_{min}$ values given in Table 3, the magnetic susceptibility anisotropy of the four meteorites is rather moderate compared with similar data observed by HAMANO and YOMOGIDA (1982) for 11 Antarctic stony meteorites, in which $(\chi_{max}-\chi_{min})/\chi_{min}>0.4$ for 5 meteorites and $(\chi_{max}-\chi_{min})/\chi_{min}>0.3$ for 10 meteorites. It seems, however, that the observed magnetic susceptibility anisotropy of Mt. Baldr b and ALH-769 is still meaningful.

If the susceptibility anisotropy of these meteorites is attributable to the average shape anisotropy of ferromagnetic metallic grains, then

$$\frac{\chi_{max}}{\chi_{min}}=\frac{1+\kappa\bar{N}_{max}}{1+\kappa\bar{N}_{min}}, \tag{9}$$

where κ, $\bar{N}_{max}$ and $\bar{N}_{min}$ denote respectively isotropic magnetic susceptibility of metal per unit volume, and the maximum and minimum values of demagnetizing factor of metallic grains depending on their average shape. As $\kappa\gg1$ and $N_{min}>1$ for Fe-Ni grains in meteorites, eq. (9) can be approximated by

$$\chi_{max}/\chi_{min}=\bar{N}_{max}/\bar{N}_{min}. \tag{9*}$$

The ratio $\bar{N}_{max}/\bar{N}_{min}$ estimated from the observed values of χ_{max}/χ_{min} for the four stony meteorites, given in Table 3, ranges between 1.22 and 1.39. Corresponding to the estimated values of $\bar{N}_{max}/\bar{N}_{min}$, the dimension ratio (*i.e.* ratio of the largest diameter to the smallest diameter) of metallic grains of both prolate and oblate shapes ranges between about 1.1 and 1.3.

It is practically impossible to statistically detect such a small shape anisotropy of metallic grains within the texture of these meteorites under a microscope. In other words, the magnetic susceptibility anisotropy can represent the statistically averaged shape anisotropy of metallic grains which is probably due to a plastic deformation of the meteorite caused by mechanical stresses.

5. Concluding Remarks

As possible effects of mechanical stresses upon the magnetic properties of stony meteorites, the piezo-remanent magnetization, a change of magnetic susceptibility caused by loading mechanical stress and the magnetic susceptibility anisotropy are discussed for typical examples in the present short note. Both the reproducible phenomena of PRM and $\chi(P)$ may be called the piezomagnetic characteristics of the meteorite samples. The magnetic susceptibility anisotropy is fundamentally different in its category from PRM and $\chi(P)$ phenomena, but it is almost certain that the magnetic anisotropy is also a result of effects of mechanical stresses on meteorites.

It is expected that quantitative characteristics of PRM and $\chi(P)$ depend on those of the magnetic susceptibility anisotropy. We recommend, therefore, that future studies on PRM and $\chi(P)$ phenomena take into consideration the anisotropic character of the magnetic properties of meteorites.

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