SHOCK REMANENT MAGNETIZATION OF METEORITES

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Abstract: The isothermal remanent magnetization (IRM), $J_R(H_+H_0)$, the shock remanent magnetization (SRM), $J_R(H_+SH_0)$, and IRM with an advance shock, $J_R(SH_+H_0)$, acquired in a magnetic field H and with a shock momentum S, are experimentally examined for two stony meteorites, Yamato-75097 L4 chondrite and Jilin H chondrite.

Just as in the case of terrestrial igneous rocks, stony meteorites can acquire the characteristic magnetizations in a small magnetic field and with a large value of S in such forms as expressed by $J_R(H_+SH_0)\simeq KSH>J_R(H_+H_0)$ and $J_R(SH_+H_0)\simeq FSH>J_R(H_+H_0)$, where $F\simeq(1/3)K$. If we assume that a stony meteorite is impacted by a mechanical shock of P in maximum compressive shock pressure in non-magnetic extraterrestrial space and then enters the geomagnetic field of 0.5 Oe, P is estimated to be 3 kbars and 0.63 kbars for the Jilin and the Yamato-75097 respectively.

Both the chondrites have the same anisotropic characteristics of $J_R(H_+H_0)$, $J_R(H_+SH_0)$ and $J_R(SH_+H_0)$ as their magnetic susceptibility.

1. Introduction

The shock remanent magnetization (SRM) of terrestrial igneous rocks has been studied in some detail (NAGATA, 1971). Denoting the application of a compressive shock by S and a magnetic field by H_+ and the release of the magnetic field by H_0, there are three possible sequences for applying S, H_+ and H_0 to a rock specimen; namely, (SH_+H_0), (H_+SH_0) and (H_+H_0S). If there is no operation of a shock (S), the ordinary isothermal remanent magnetization (IRM) acquired by applying a magnetic field can be expressed as $J_R(H_+H_0)$. The remanent magnetization acquired by the operation (SH_+H_0) can be expressed as $J_R(SH_+H_0)$, which is referred to as "IRM with an advance shock", where the operation S occurs in non-magnetic space. $J_R(H_+SH_0)$ is the shock remanent magnetization and $J_R(H_+H_0S)$ is the shock demagnetization of IRM, $J_R(H_+H_0)$.

It has been experimentally demonstrated for terrestrial igneous rocks (NAGATA, 1971) that SRM, $J_R(H_+SH_0)$, is approximately proportional to both H and S if H is small and S is sufficiently large, whereas $J_R(SH_+H_0)\rightarrow J_R(H_+H_0)$ when $S\rightarrow$O. It seems likely that SRM may have to be taken into consideration, in particular, in the case of meteorite paleomagnetism, since petrological and mineralogical evidence of repeated severe mechanical impacts of meteorites have been reported. There is a possibility that an intense remanent magnetization could be acquired by a meteorite body if it is strongly impacted even in the presense of a very weak magnetic field.

Since the piezo-remanent magnetization (PRM) which is acquired by a rock sample by uniaxially compressing by presure P (P_+ for operational symbol) and then releasing P (P_0 for operational symbol) in the presence of a magnetic field H, is essentially the same as SRM, provided that the momentum of the compressive shock S is expressed as

$$S=\int_t P(t)\,\mathrm{d}t\,, \qquad (1)$$

where t denotes time. PRM which can be symbolically expressed by $J_R(H_+P_+P_0H_0)$ is approximately equal to SRM, when the maximum value of $P(t)$ is equal to P in the same magnetic field, H (NAGATA, 1971). In a previous paper, (NAGATA *et al.*, 1982), the PRM characteristics of 3 Antarctic stony meteorites were reported. In the present note, the SRM characteristics of meteorites will be discussed on the basis of new experimental data.

IRM with an advanced shock, $J_R(SH_+H_0)$, is particular interest in the case of meteorites, because meteorites which were severely impacted in extraterrestrial space where the magnetic field is negligibly weak, could acquire an intense remanent magnetization as J_R (SH_+H_0) when it enters the magnetic field of the earth. It has been experimentally demonstrated that both $J_R(SH_+H_0)$ and $J_R(P_+P_0H_+H_0)$ of terrestrial igneous rocks are larger than $J_R(H_+H_0)$ and they are approximately proportional to the magnitude of S or P when S or P is sufficiently large relative to H (NAGATA and CARLETON, 1969 a; NAGATA, 1971). The NAGATA-CARLETON theory of $J_R(SH_+H_0)$ and $J_R(P_+P_0H_+H_0)$ (NAGATA and CARLETON, 1969b) suggests that the effect of an advance shock on IRM should be present in the case of stony meteorites. An experimental verification of J_R (SH_+H_0) for meteorites is given in the present work.

In a previous paper (NAGATA *et al.*, 1982), it has been noted that the magnetic anisotropy of stony meteorites is quite large in general, so that the anisotropy characteristics must be taken into account in dealing with IRM, SRM and PRM of stony metorites. In the present work, therefore, the basic parameters of magnetic anisotropy of meteorite samples were first determined in terms of the magnetic susceptibility anisotropy, and these parameters are taken into consideration in dealing with their $J_R(H_+H_0)$, $J_R(H_+SH_0)$ and $J_R(SH_+H_0)$.

2. Instrumentations

The instrument used to apply a compressive shock on meteorite samples with or without an ambient magnetic field is essentially the same as a "bashometer" described by NAGATA (1971). The shock momentum (S) of a falling mass (m) upon a rock specimen is given by

$$S=m\sqrt{2hg}\,, \qquad (2)$$

where h and g denote respectively the vertical distance from the starting height of a falling mass to the surface of an examined sample and the acceleration due to gravity.

The wave form of $P(t)$ defined by eq. (1) consists of a main pulse peak and a considerably smaller second peak which corresponds to a reflection of the main pulse from the bottom base of the bashometer. The half-value width of the main pulse is about 0.4 ms in the experiment described here. Approximately speaking, therefore, $S \simeq P_m \cdot \Delta t$ with $\Delta t = 0.4$ ms, where P_m denotes the peak value of the main pulse. With this degree of approximation, $J_R(H_+SH_0)$ is roughly the same as $J_R(H_+P_+P_0H_0)$ with $P = S/\Delta t$. The approximate identity between SRM and PRM has been experimentally verified on an H chondrite (Jilin), as discussed later. It has been experimentally confirmed that Δt is practically constant for a range of S corresponding to a range of h from 1 cm to 10^2 cm (*e.g.* NAGATA, 1971).

The remanent magnetization at various stages was measured by a cryogenic magnetometer and the anisotropic magnetic susceptibility by an alternating field magnetic bridge with 0.2 Oe of peak magnetic field intensity.

3. Anisotropic Magnetic Susceptibility and Anisotropic IRM

Test specimens of meteorites of cubic form are cut from meteorite pieces of irregular form, so that one of the three axes of the cube is approximately parallel to the axis of the maximum magnetic susceptibility. As shown in Figs. 1 and 2, however, the results of precise measurements of the anisotropic magnetic susceptibility of these speciments of cubic form do not satisfy the required condition particularly well.

In the top part of Figs. 1 and 2, the magnetic susceptibility distribution within three planes perpendicular to the three axes (x, y, z) of cubic specimens, $\chi(y, z)$, $\chi(z, x)$ and $\chi(x, y)$, are illustrated, where $\chi(x\text{-}x)$, $\chi(y\text{-}y)$ and $\chi(z\text{-}z)$ are the magnetic susceptibility values along the three axes, (x, y, z). It was planned that the three axes (x, y, z) would coincide with the three principal axes of magnetic anisotropy ellipsoid. Although the orientation of the three axes, (x, y, z) in the present experiments is not precisely along the principal axes, the average magnetic susceptibility along the three axes of two chondrites, Yamato-75097 chondrite (YANAI, 1979) and Jilin H chondrite (JILIN METEORITE SHOWER ED. COMM., 1979), have been determined as given in Table 1. The maximum (χ_{max}) and minimum (χ_{min}) susceptibilities are 7.82×10^{-3} and 5.90×10^{-3} emu/Oe/g respectively for the Yamato-75097 chondrite and 2.55×10^{-3} and 2.12×10^{-2} emu/Oe/g respectively for the Jilin chondrite, and therefore $(\chi_{max} - \chi_{min})/\chi_{min} = 0.325$ for the Yamato-75097 and $(\chi_{max} - \chi_{min})/\chi_{min} = 0.203$ for the Jilin meteorite.

IRMs along the three axes (x, y, z) of these two chondrites are illustrated in Figs. 1 and 2. The IRM *vs.* H curves are approximately represented by

$$J_R(H_+H_0) = bH^k, \tag{3}$$

where k is empirically determined as $k = 1.57$ for the Yamato-75097 and $k = 1.42$ for the Jilin. Then, the b values derived from these IRM *vs.* H curves with the aid of eq. (3) are given in Table 1. In both cases, the Yamato-75097 and the Jilin, $b_z > b_x > b_y$ corresponding to the sequence $\chi(z\text{-}z) > \chi(x\text{-}x) > \chi(y\text{-}y)$.

As suggested previously (HAMANO and YOMOGIDA, 1982; NAGATA *et al.*, 1982), the anisotropy of magnetic susceptibility of stony meteorites is probably due to the shape anisotropy of metallic grains resulting in an anisotropic orientation for the demagnetizing factor of these metallic grains. IRM should also be controlled by the anisotropic orientation of the demagnetizing factor, as the present experimental results demonstrate.

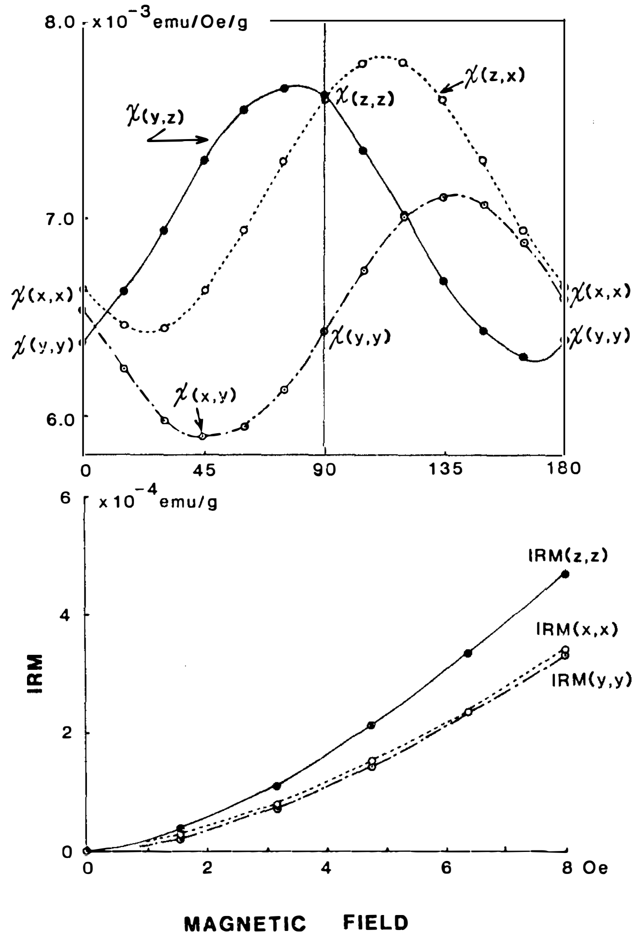


Fig. 1. Magnetic susceptibility around (x, y, z)-axes of Yamato-75097 chondrite (top) and isothermal remanent magnetization along the three axes (bottom).

Table 1. Anisotropic magnetic susceptibility and anisotropic IRM of chondrites.

Observed parameters	Y-75097	Jilin	Unit
(Magnetic susceptibility)			
χ (x-x)	6.68×10^{-3}	2.39×10^{-2}	emu/Oe/g
χ (y-y)	6.53×10^{-3}	2.21×10^{-2}	//
χ (z-z)	7.60×10^{-3}	2.46×10^{-2}	//
$(\chi_{max}-\chi_{min})/\chi_{min}$	0.325	0.203	
(IRM)			
b_x	1.287×10^{-5}	4.21×10^{-4}	emu/g/Oe^k
b_y	1.264×10^{-5}	3.90×10^{-4}	//
b_z	1.819×10^{-5}	4.67×10^{-4}	//
k	1.57	1.42	

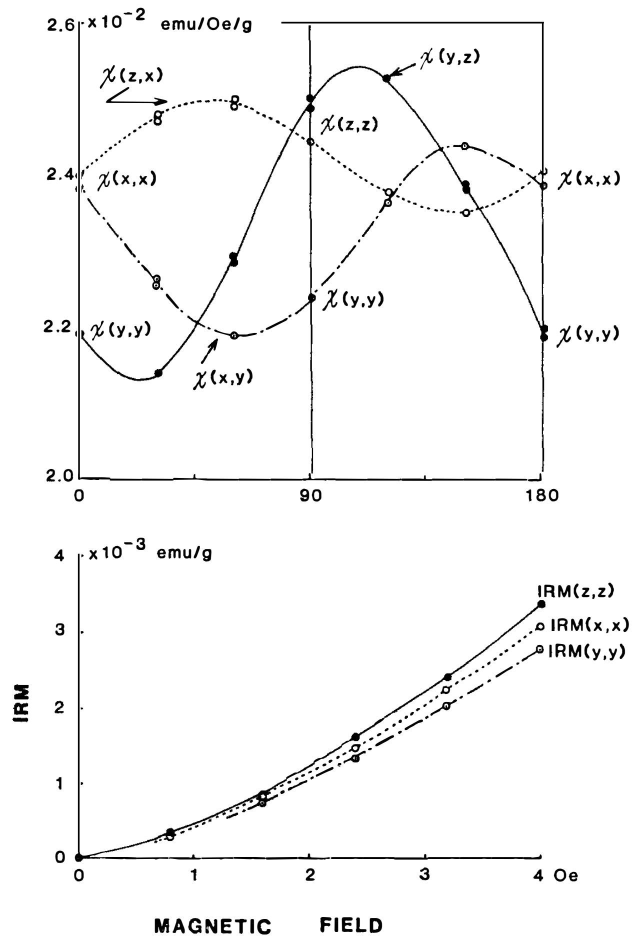


Fig. 2. Magnetic susceptibility around (x, y, z)-axes of Jilin chondrite (top) and isothermal remanent magnetization along the three axes (bottom).

4. Shock Remanent Magnetization

The intensity of SRM, $J_R^{/\!/}(H_+SH_0)$, acquired by a constant shock momentum (S) in the presence of magnetic fields (H) of various intensities, is plotted against H for the two chondrites in Figs. 3 and 4, where $J_R^{/\!/}$ indicates that the direction of uniaxial shock is parallel to the direction of applied magnetic field. The shock momentum, S, is estimated by eq. (2), where $m=198.6$ g. Since $\Delta t=4.0\times10^{-4}$ s, the maximum compressive pressure (P) of a shock of S in momentum is approximately given by $P=S/\Delta t=2.38\times10^{3}\,S$ bar.

In order to compare $J_R^{/\!/}(H_+SH_0)$ with $J_R^{/\!/}(H_+P_+P_0H_0)$, $J_R^{/\!/}(H_+P_+P_0H_0)$ of the Jilin chondrite along the z-axis as function of H and of P were examined, the result being shown in Figs. 5a and 5b. From these experimental results, it may be concluded that

$$J_R^{/\!/}(H_+P_+P_0H_0)\simeq CPH\,, \qquad (4)$$

for small values of H and large values of P in the case of stony meteorites, just as in the case of terrestrial igneous rocks. For the z-component of the Jilin meteorite, C is ap-

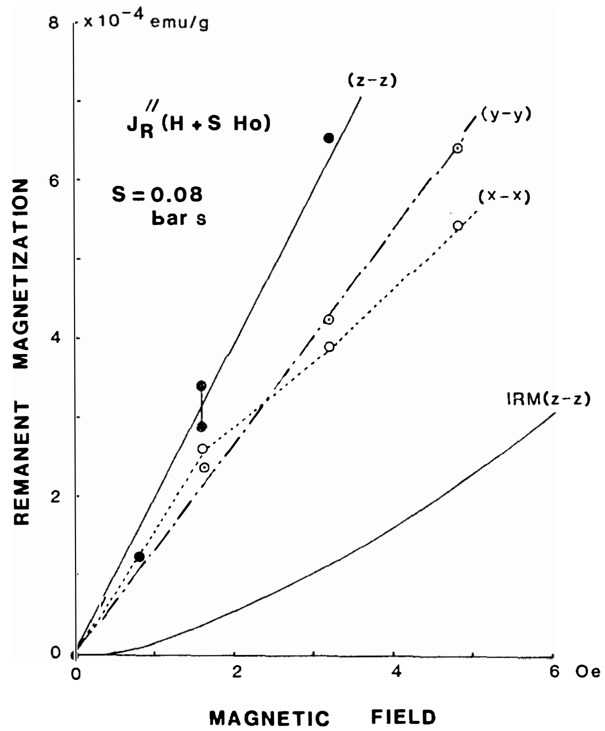


Fig. 3. Shock remanent magnetization along (x, y, z)-axes of Yamato-75097 (L4) chondrite for a constant shock momentum (S) and different magnetic fields.

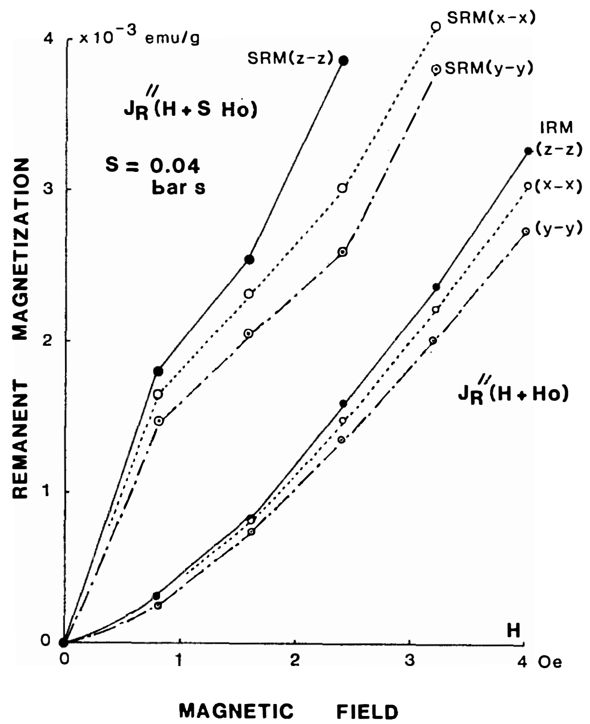
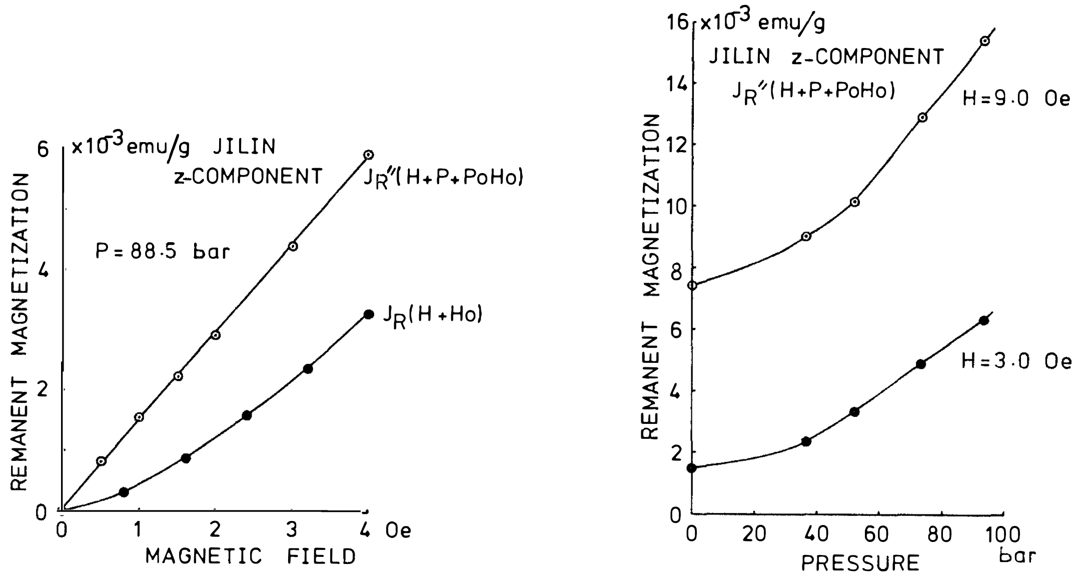


Fig. 4. Shock remanent magnetization along (x, y, z)-axes of Jilin (H) chondrite for a constant shock momentum (S) and different magnetic fields.



(*a*) $J_R^{\prime\prime}(H_+P_+P_0H_0)$ *vs.* H *with a constant value of* $P(P=88.5$ *bar)* *in comparison with IRM.*

(*b*) $J_R^{\prime\prime}(H_+P_+P_0H_0)$ *vs.* P *for* $H=3$ *Oe and* $H=9$ *Oe.*

Fig. 5. Piezo-remanent magnetization along z-axis of Jilin chondrite.

proximately given by $C=1.85\times10^{-5}$(emu/g)/bar Oe.

$J_R^{\prime\prime}(H_+SH_0)$ of the Jilin illustrated in Fig. 4 is not linearly dependent on H, probably because exact reproducibility of the shock momentum (S) is not accurate due to random errors. For the z-component, however, $J_R^{\prime\prime}(H_+SH_0)$ is approximately expressed as $J_R^{\prime\prime}(H_+SH_0)\simeq(1.7\times10^{-3}$ emu/g/Oe$)\times H$ for $S=4\times10^{-2}$ bar s. Using the coefficient (C) of $J_R(H_+P_+P_0H_0)$, then, the S-value for $J_R^{\prime\prime}(H_+SH_0)$ corresponds to $P=92$ bar for the equivalent PRM given by eq. (4). This gives $\Delta t=S/P=4.2\times10^{-4}$ s. The Δt value thus derived by comparing SRM and PRM is in reasonably good agreement with the directly observed value (0.4 ms) of a shock pulse width. It seems likely therefore that the simpler experimental procedures for generating PRM can replace those used to generate SRM in order to examine the effects of mechanical compression (including compressive shocks) upon the remanent magnetization of rocks. Precise repeats of the same value of S are subject to much experimental difficulty as a result of slight differences in the conditions.

Even taking into consideration possible errors in S in the present experimental procedures, Figs. 3 and 4 clearly show that $J_R^{\prime\prime}(H_+SH_0)$ is much larger than $J_R(H_+H_0)$ acquired in the same magnetic field (H), and that $J_R^{\prime\prime}(H_+SH_0)$ is approximately proportional to H when S is constant and sufficiently large. Figure 6 shows an example of the dependence of $J_R^{\prime\prime}(H_+SH_0)$ upon S for a constant magnetic field, where $J_R^{\prime\prime}(H_+SH_0)$ is approximately proportional to S. It has been concluded in the case of terrestrial igneous rocks (NAGATA, 1971) that

$$J_R^{\prime\prime}(H_+SH_0)\simeq KHS\,,\quad \text{for}\quad H<H_c(S)\quad\text{and}\quad S>S_c(H)\,,\qquad (5)$$

where $H_c(S)$ and $S_c(H)$ denote respectively a certain critical value of H depending on

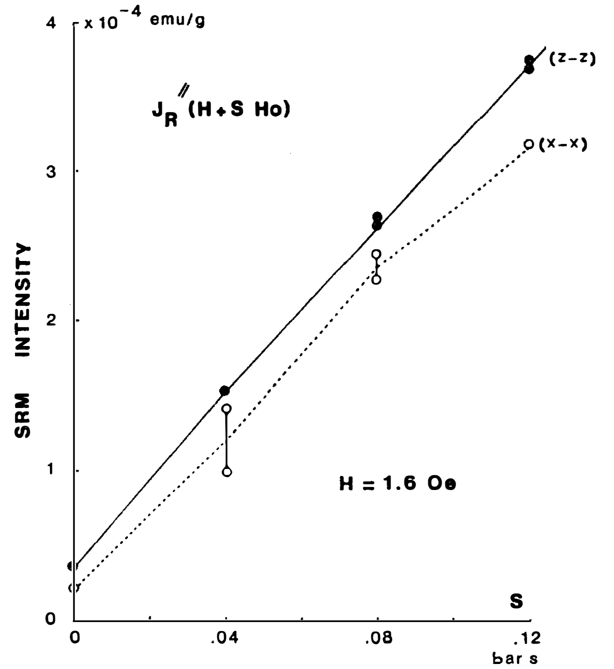


Fig. 6. Shock remanent magnetization x- and z-axes of Yamato-75097 (L4) chondrite for a constant value of H and different values of P.

S and a critical value of S depending on H. It may be concluded then that characteristics of $J_R^{/\!/}(H_+SH_0)$ are essentially the same in both terrestrial igneous rocks and stony meteorites. For terrestrial igneous rocks, $J_R{}^{\perp}(H_+SH_0)$ which is the SRM for the case of the shock perpendicular to the direction of the field generally given by

$$J_R{}^{\perp}(H_+SH_0)=\frac{3}{4}J_R^{/\!/}(H_+SH_0)\,. \tag{6}$$

This relation should be holds in the case of stony meteorites.

A newly observed characteristic of $J_R(H_+SH_0)$ of stony meteorites is its anisotropic behavior, which is represented by $[J_R^{/\!/}(H_+SH_0)]_z>[J_R^{/\!/}(H_+SH_0)]_x>[J_R^{/\!/}(H_+SH_0)]_y$ corresponding to $\chi(z\text{-}z)>\chi(x\text{-}x)>\chi(y\text{-}y)$ in Fig. 4, where the ratio $[J_R^{/\!/}(H_+SH_0)]_x$: $[J_R^{/\!/}(H_+SH_0)]_y$: $[J_R^{/\!/}(H_+SH_0)]_z$ is approximately equal to $\chi(x\text{-}x)$: $\chi(y\text{-}y)$: $\chi(z\text{-}z)$. Although the observed curve of $[J_R^{/\!/}(H_+SH_0)]_x$ *vs.* H of the Yamato-75097 chondrite, shown in Fig. 3, has a low field crossover, over most of the range $[J_R^{/\!/}(H_+SH_0)]_z>$ $[J_R^{/\!/}(H_+SH_0)]_x$ and $[J_R^{/\!/}(H_+SH_0)]_z>[J_R^{/\!/}(H_+SH_0)]_y$ corresponding to $\chi(z\text{-}z)>\chi(x\text{-}x)$ and $\chi(z\text{-}z)>\chi(y\text{-}y)$. The coefficients ($K$) defined by eq. (5) along the three axes of the two chondrites are given in Table 2. The coefficients (C) of the equivalent PRM ($J_R^{/\!/}(H_+P_+P_0H_0)$) derived assuming that $\Delta t=0.42$ ms are also given. The coefficients $K(x\text{-}x)$ and $C(x\text{-}x)$ of the Yamato-75097 in Table 2 are evaluated by taking into account the experimental results given by Fig. 6. The proposed model of the shape anisotropy of metallic grains resulting in the anisotropy of effective magnetic field intensity in stony meteorites may also explain the observed anisotropic behavior of SRM.

Table 2. Anisotropic SRM.

Parameters	Y-75097	Jilin	Unit
K (x-x)	(2.00×10^{-3})	3.20×10^{-2}	emu/g/Oe bar s
K (y-y)	1.75×10^{-3}	2.80×10^{-2}	〃
K (z-z)	2.46×10^{-3}	4.42×10^{-2}	〃
C (x-x)	(8.4×10^{-7})	1.34×10^{-5}	emu/g/Oe bar
C (y-y)	7.4×10^{-7}	1.18×10^{-5}	〃
C (z-z)	10.4×10^{-7}	1.86×10^{-5}	〃

5. IRM with an Advance Shock

A particular interest of the effect of a mechanical shock on the magnetization of stony meteorites concerns the possible memory of a previous mechanical shock when a magnetic field is applied at a later stage; namely, an effect of advance shock on the final magnetization. For terrestrial igneous rocks, the effect of advance shock on magnetization has been demonstrated by the experimental result that $J_R(SH_+H_0)>J_R(H_+H_0)$ and that $J_R(SH_+H_0)$ increases with increasing S (*e.g.* NAGATA, 1971, 1974). This effect may occur in stony meteorites also, because the mechanism of acquisition of $J_R(SH_+H_0)$ has been shown to be equivalent to that of $J_R(P_+P_0H_+H_0)$. $J_R(P_+P_0H_+H_0)$ characteristics have been theoretically verified for a random assemblage of a large number of ferromagnetic grains such as natural rocks and stony meteorites (NAGATA and CARLETON, 1969b).

If a stony meteorite block is severely impacted in extraterrestrial space where the present magnetic field is only about 10^{-4} Oe and the meteorite then enters the geomagnetic field, it will acquire $J_R(SH_+H_0)$, where S is the shock momentum given in the ex-

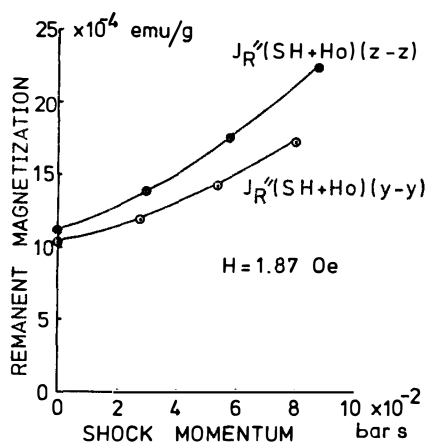


Fig. 7. IRM with an advanced shock (S) along y- and z-axes of Jilin chondrite for a constant magnetic field and different values of S.

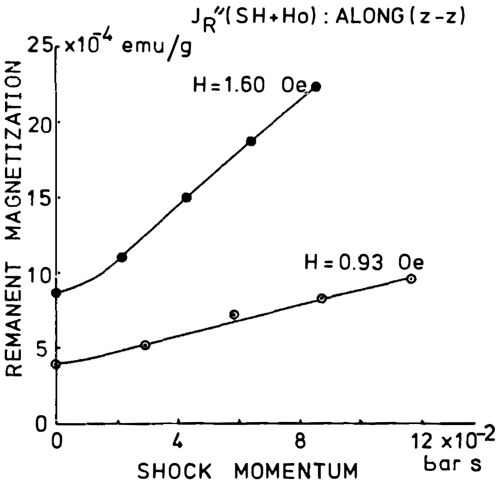


Fig. 8. IRM with an advanced shock $J_R''(SH_+H_0)$, along z-axis of Jilin chondrite dependent on shock momentum and magnetic field.

traterrestial space and H is the geomagnetic field intensity. From this viewpoint, the characteristics of $J_R(SH_+H_0)$ of meteorites will be of special interest.

Figure 7 shows an example of $J_R^{\parallel}(SH_+H_0)$ *vs.* S curves of the Jilin chondrite along its y- and z-axes. S is applied to the chondrite specimen in a non-magnetic space, with a magnetic field less than 5×10^{-3} Oe. Figure 8 shows another set of examples of the $J_R^{\parallel}(SH_+H_0)$ *vs.* S curves along the z-axis of the Jilin chondrite. These experimental results indicate that $J_R(SH_+H_0)$ increases with increasing S when H is kept constant, approaching an asymptotic value, which can probably be expressed by

$$J_R^{\parallel}(SH_+H_0)\simeq FSH\,, \tag{7}$$

where F is a material constant. This was reported for terrestrial igneous rocks (NAGATA, 1971), and was predicted by the NAGATA-CARLETON theory for $J_R(P_+P_0H_+H_0)$ (1969 b). Figure 7 further indicates that the magnetically anisotropic behavior of a stony meteorite is reflected on its $J_R(SH_+H_0)$. The anisotropic characteristic of $J_R(SH_+H_0)$ may be reasonably well explained on the basis of anisotropic effective magnetic field caused by the shape anisotropy.

6. Concluding Remarks

In the present work, the shock remanent magnetization, $J_R(H_+SH_0)$, and IRM with an advance shock, $J_R(SH_+H_0)$, of stony meteorites are semi-quantitatively demonstrated. As already mentioned, precise quantitative studies of $J_R(H_+SH_0)$ and $J_R(SH_+H_0)$ are difficult. It is suggested therefore that quantitative examinations of the effects of compressive shocks on meteorite magnetization can be better performed by experimentally examining the effects of static compressions on meteorite magnetization, such as $J_R(H_+P_+P_0H_0)$ and $J_R(P_+P_0H_+H_0)$. It is shown that the effects of S on rock magnetization can be related to these of P using the relation

$$S=\int P(t)\,\mathrm{d}t\simeq P_{\max}\Delta t\,.$$

The major results of the present study are that stony meteorites also can acquire $J_R(H_+SH_0)$ and $J_R(SH_+H_0)$ as a result both of a compressive mechanical shock (S) in the presence of a magnetic field and as an after-effect of S when the magnetic field is applied later. They are approximately equivalent to $J_R(H_+P_+P_0H_0)$ and $J_R(P_+P_0H_+H_0)$ respectively with respect to the physical mechanism of their acquisition. It is also a new result of the present study that the magnetic anisotropic characteristics of stony meteorites are in the same sense as the magnetic susceptibility anisotropy (χ), $J_R(H_+H_0)$, $J_R(H_+SH_0)$ and $J_R(SH_+H_0)$.

Dealing with the qualitative aspects of the present experimental results the following points may be made.

(i) Relationship between $J_R(SH_+H_0)$ and $J_R(H_+SH_0)$

The NAGATA-CARLETON theory (1969a, b) of $J_R(P_+P_0H_+H_0)$ and $J_R(H_+P_+P_0H_0)$ of natural rocks has shown that a theoretical relation between the coefficient K in eq. (5) and F in eq. (7) given by

$$F=\frac{1}{3}K\,. \tag{8}$$

$F(z\text{-}z)$ for the Jilin meteorite is 1.30×10^{-2} emu/g/Oe bar s, as given in Table 2. The experimental value, $F(z\text{-}z)/K(z\text{-}z)=0.29$ for the Jilin chondrite gives the same value as the theoretical value given by eq. (8).

(ii) Possible magnitude of shocks on meteorites

If we assume that the Jilin chondrite has been compressively impacted by P in uniaxial pressure along the z-axis in non-magnetic extraterrestrial space and then it entered the geomagnetic field of 0.5 Oe, $J_R^{//}(SH_+H_0)=2.73\times10^{-6}P$ (bar) emu/g is expected to be acquired. The observed intensity of natural remanent magnetization (NRM) of the Jilin chondrite is 8.38×10^{-3} emu/g and the AF-demagnetizing field intensity ($\tilde{H}_{1/2}$) to reduce the NRM intensity to a half of the initial value is only 55 Oe peak. If the observed NRM of the Jilin chondrite is entirely attributed to $J_R(SH_+H_0)$, the resulting P value is $P=3$ kbars. This is a reasonable value. If, alternatively, the observed NRM were attributed to SRM acquired by $P=10$ kbars along the z-axis, the ambient magnetic field (H^*) is estimated as $H^*=4.5\times10^{-2}$ Oe. This case can not be rejected.

For the Yamato-75097 chondrite, the NRM intensity is 8.44×10^{-5} emu/g and $\tilde{H}_{1/2}=20$ Oe peak. If the observed NRM of the Yamato-75097 chondrite is attributed to $J_R(SH_+H_0)$ along the z-axis and $H=0.5$ Oe, then P is estimated as $P=650$ bars. If the same NRM is attributed to $J_R(H_+{}^*SH_0{}^*)$ along the z-axis and P assumes 10 kbars, H^* is evaluated as $H^*=8\times10^{-3}$ Oe. Both cases can explain the remanent magnetization observed.

(iii) Anisotropic magnetization

For both the Yamato-75097 and the Jilin chondrites examined in the present study, $[J_R(H_+H_0)]_z>[J_R(H_+H_0)]_x>[J_R(H_+H_0)]_y$ and $[J_R^{//}(H_+SH_0)]_z>[J_R^{//}(H_+SH_0)]_x>[J_R^{//}(H_+SH_0)]_y$ corresponding to $\chi(z\text{-}z)>\chi(x\text{-}x)>\chi(y\text{-}y)$. At the present stage, the observed magnetic anisotropy is interpreted as due to the anisotropy in the effective magnetic field ($H_{\rm eff}$) caused by the shape anisotropy of metallic grains. If so, it can be theoretically expected that $[J_R^{//}(H_+SH_0)]_x : [J_R^{//}(H_+SH_0)]_y : [J_R^{//}(H_+SH_0)]_z=\chi(x\text{-}x) : \chi(y\text{-}y) : \chi(z\text{-}z)$, and $[J_R(H_+H_0)]_x : [J_R(H_+H_0)]_y : [J_R(H_+H_0)]_z=[\chi(x\text{-}x)]^k : [\chi(y\text{-}y)]^k : [\chi(z\text{-}z)]^k$. It does not seem, however, that the present experimental results are sufficiently precise to establish the expected quantitative relationship.

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