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Hysteresis properties of chondritic meteorites: New results for chondrules from the Allende meteorite

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RESUMEN

Se presentan los resultados iniciales del estudio de propiedades magnéticas (histéresis magnética) de veinte cóndrulos provenientes de un fragmento de 50 cm^3 del meteorito Allende, cuyos diámetros reportados son del orden de 0.08 a 0.44 cm. Los resultados documentan una gran variación en los parámetros de histéresis, los cuales contribuyen a hacer este meteorito magnéticamente complejo. La fuerza coercitiva (Hc) varía de unos 4 mT hasta cerca de 32.5 mT. El cociente entre la remanencia magnética a la saturación magnética (Mr/Ms) varía entre 0.025 y 0.25. Si la magnetita es el mineral magnético principal en los cóndrulos, entonces la variación de sus parámetros de histéresis sugiere la existencia de un rango en los tamaños de granos (y formas), los cuales corresponden a estados de dominio pseudosencillo (PSD) y multidominio (MD). No ha sido posible documentar ningún cóndrulo en estado de dominio sencillo (SD). Nuestro estudio permite contemplar relaciones simples entre masa, densidad, dimensiones, formas de los cóndrulos, y propiedades magnéticas de histéresis. Se pueden distinguir tres grupos con valores característicos de coercitividad: (a) grupo 1 para cóndrulos con Hc entre 0 5 y 5 mT; (b) grupo 2 para aquéllos con valores de Hc entre 5 y 15 mT; y (c) grupo 3 para aquéllos con valores mayores de 15 mT. Los cóndrulos del grupo 1 corresponden al campo MD, los cóndrulos del grupo 2 en el campo intermedio PSD para bajos valores de la razón Mr/Ms, y el grupo 3 en el campo PSD con valores elevados de Mr/Ms.

PALABRAS CLAVE: Meteorito Allende, magnetismo de rocas, meteoritos condríticos, Nebulosa Solar.

ABSTRACT

Hysteresis properties of twenty individual chondrules from a ~50 cc piece of the Allende carbonaceous chondritic meteorite, with diameters between about 0.08 and 0.44 cm are reported. Coercive force Hc varies from about 3 mT to 32.5 mT. Magnetic remanence to saturation magnetization ratios Mr/Ms vary from about 0.025 to 0.25. If magnetite is the main magnetic mineral, then this variation in hysteresis parameters suggests a range of particle grain sizes and shapes, corresponding to pseudo-single domain PSD and multidomain MD states. No chondrules with single domain SD states were observed. Simple relationships among mass, density, size and shape of chondrules and magnetic hysteresis properties are proposed. Three groups with characteristic coercitivity values are distinguished: (a) group 1 for chondrules with Hc between 0 and 5 mT; (b) group 2 for those with Hc between 5 and 15 mT; and (c) group 3 for those with Hc larger than 15 mT. Group 1 chondrules plot within the MD field, group 2 chondrules plot in the PSD and intermediate fields with low Mr/Ms values, and group 3 chondrules plot in the PSD field with high Mr/Ms values.

KEY WORDS: Allende meteorite, rock-magnetism, chondritic meteorites, chondrules, Solar Nebula.

INTRODUCTION

The magnetic properties of chondritic meteorites have implications for our understanding of the magnetic fields in the primitive solar nebula and the exploration of the origin of the solar system (e.g., Banerjee and Hargraves, 1972; Lanoix *et al*., 1978; Sugiura *et al*., 1979). Carbonaceous chondrites are considered to provide the most reliable paleomagnetic records (Sugiura and Strangway, 1988). Magnetic field intensity estimates derived from bulk chondritic meteorite samples (matrix plus chondrules) using the Thellier-Thellier paleointensity method gave relatively consistent low values of around 0.1 mT (Banerjee and Hargraves, 1972; Brecher, 1972). In contrast, studies on chondrules resulted in higher paleointensity estimates, up to 1.6 mT (Lanoix *et al*., 1978). Nagata (1979) used an anytheretic remanent magnetization (ARM) method and obtained also large paleointensity values of 0.73 mT. The large paleointensity fields of around 1 mT and the apparent discrepancies in the analytical data prompted additional studies. Sugiura *et al*. (1979) analyzed the magnetic properties of chondrules and concluded that they carry both pre- and post-accretional remanent magnetization components and provided support for the high paleointensity estimates for the primitive solar nebula. Wasilewski (1981), on the other hand, criticized the application of the Thellier-Thellier method because of the complexity of magnetic properties in the Allende meteorite and suggested that the high paleointensity values were possibly due to irreversible changes at low temperatures and magnetic contamination. Other studies also documented the mineralogical complexity and the importance of metamorphic and low-temperature alteration processes likely to exert major effects on the magnetization record of the meteorites (e.g., McSween, 1979; Haggerty and McMahon, 1979; Choi *et al.*, 1997). Studies on the origin and subsequent history of chondrules have remained on the frontline of research in meteoritics and planetary sciences (e.g., King, 1983; Hewins *et al.*, 1996; Connolly and Love, 1998).

We report new results of a magnetic hysteresis property study of individual chondrules from the Allende carbonaceous chondritic meteorite (CV3), and we document a large variation in hysteresis parameters that make the bulk meteorite magnetically complex.

MEASUREMENTS

We use a fragment of the Allende meteorite from the meteoritic collection of the Institute of Astronomy, UNAM, Mexico City (Figure 1). Thin sections were prepared to investigate the petrography of the matrix and chondrules of the Allende fragment, and to search for any alteration features (Figure 2 a, b). The thin section observations also permitted to investigate variations in chondrule size and degree of sphericity (Figure 2 a, b). Figure 2 a shows a typical BO chondrule (upper right hand corner) and two PO or POP chondrules (nomenclature of McSween, 1977). A sample from the interior of the fragment, free from the fusion crust, was cut and individual chondrules were separated from the fine-grained matrix.

A total of 20 individual chondrules of different sizes were selected for the study. All chondrules were individually scanned to look for any matrix material still attached. Measurements of the radius, departure from spherical shape, weight, and volume were taken. The radius varied from about 0.04 cm to about 0.222 cm. Weights span a range from less than 0.001 grams to about 0.11 grams. Weight (W) of individual chondrules increases as a function of radius (r, in cm), as $W = 0.011 + 0.414\,r - 4.212\,r^2 + 23.163\,r^3$ (Figure 3). The density (ρ) shows a tendency to slightly decrease with increasing radius (in cm) (Figure 4). A least-squares linear fit gives $\rho = 3.523 - 6.754\,r$.

Hysteresis loops (Figure 5) and isothermal remanent magnetization (IRM) acquisition and back-field demagnetization experiments (Figure 6) were conducted using a MicroMag system. This system is ideally suited for study of microsamples, with a high analytical precision. Measurements were carried out with 5 mT increments up to maximum fields of 1 T. Hysteresis loops were corrected for paramagnetic contributions and the corresponding hysteresis parameters were calculated for before and after slope correction. Coercive force Hc and remanent coercive force Hcr, saturation field Hsat, saturation magnetization Ms, and remanent magnetization Mr were calculated from the hysteresis loops and the IRM acquisition curves. The ratios of magnetization Mr/Ms are plotted as a function of the coercivity ratio Hcr/Hc in a Day diagram (Figure 7). Individual chondrules fall in the pseudo-single domain (PSD) and multi-domain (MD) fields (Day *et al.*, 1977). No chondrules from our sample fall within the single domain (SD) field. A plot of the magnetization ratio Mr/Ms as a function of the coercive force Hc (Figure 8) allows a simple characterization of the chondrule behaviors. The magnetization ratio shows a tendency to increase as a function of coercive force, $Mr/Ms = 0.008 + 0.007\,Hc$ (Figure 8). Three groups with characteristic coercitivity Hc values are distinguished for further analysis: Group 1 for chondrules with Hc between 0 and 5 mT, group 2 for those with Hc between 5 and 15 mT, and group 3 for those with Hc larger than 15 mT (Figure 8). Group 1 chondrule plots within the MD field, group 2 chondrules plot in the PSD and intermediate fields with low Mr/Ms values, and group 3 chondrules plot in the PSD field with higher Mr/Ms values (Figure 7). Examples of hysteresis loops and IRM acquisition and demagnetization curves are shown in Figures 5 and 6, for chondrules of the three groups.

DISCUSSION

We became interested in studying the Allende meteorite in an attempt to contribute to the understanding of the Allende paleomagnetic record. Study of magnetic properties of carbonaceous chondritic meteorites has been critical to document the physical conditions (early magnetic field in the solar nebula) prevailing at the initial stages of formation of the solar system (e.g., Banerjee and Hargraves, 1972; Lanoix *et al.*, 1978; Sugiura *et al.*, 1979). Detailed study of Allende samples provides insights on the early magnetic fields, but also on a complex long-term history where secondary alteration and metamorphism may have exerted a significant influence on the paleomagnetic record (e.g., McSween, 1979). Chondrule rims have been identified in ordinary and carbonaceous chondrites, while ferromagnesian rims occur in carbonaceous chondrites that differ in composition of the chondrules (Rubin, 1984; Prinz *et al.*, 1986; Kring, 1991). The rim textures have been interpreted in terms of high temperatures and oxidizing environments in a chemically heterogeneous solar nebula (Kring, 1991).

Fig. 1. Partial view of the sample from the Allende carbonaceous chondritic meteorite (Collection of Meteorites, UNAM, Institute of Astronomy).

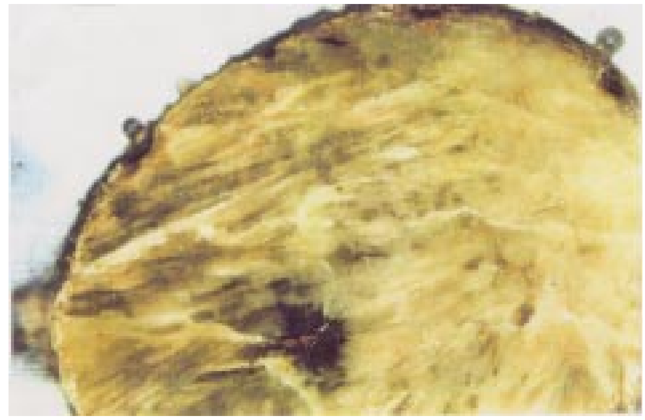


Fig. 2. (a) Thin section of an Allende sample showing chondrules and matrix.

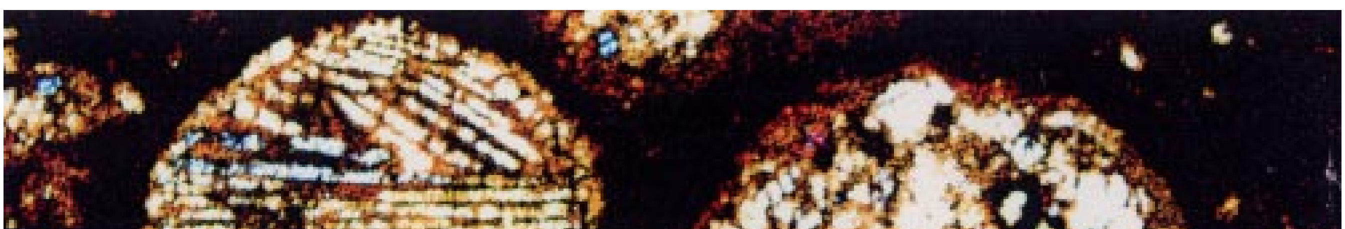


Fig. 2. (a) (b) Chondrules of the Allende meteorite, with a typical BO chondrule (upper right hand corner) and two PO or POP chondrules (nomenclature of McSween, 1977).

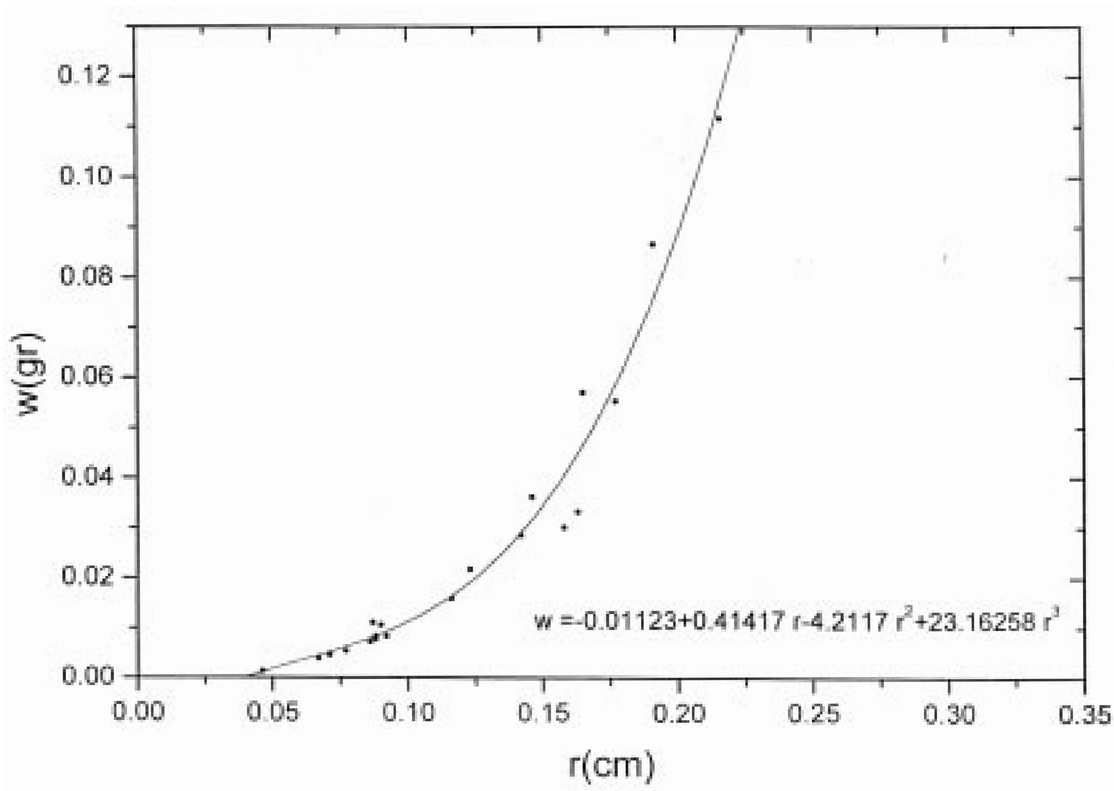


Fig. 3. Plot of the weight (W in grams) of individual chondrules as a function of radius (r in cm). Weight increases with chondrule size following a relationship here fitted with a three-degree polynomial.

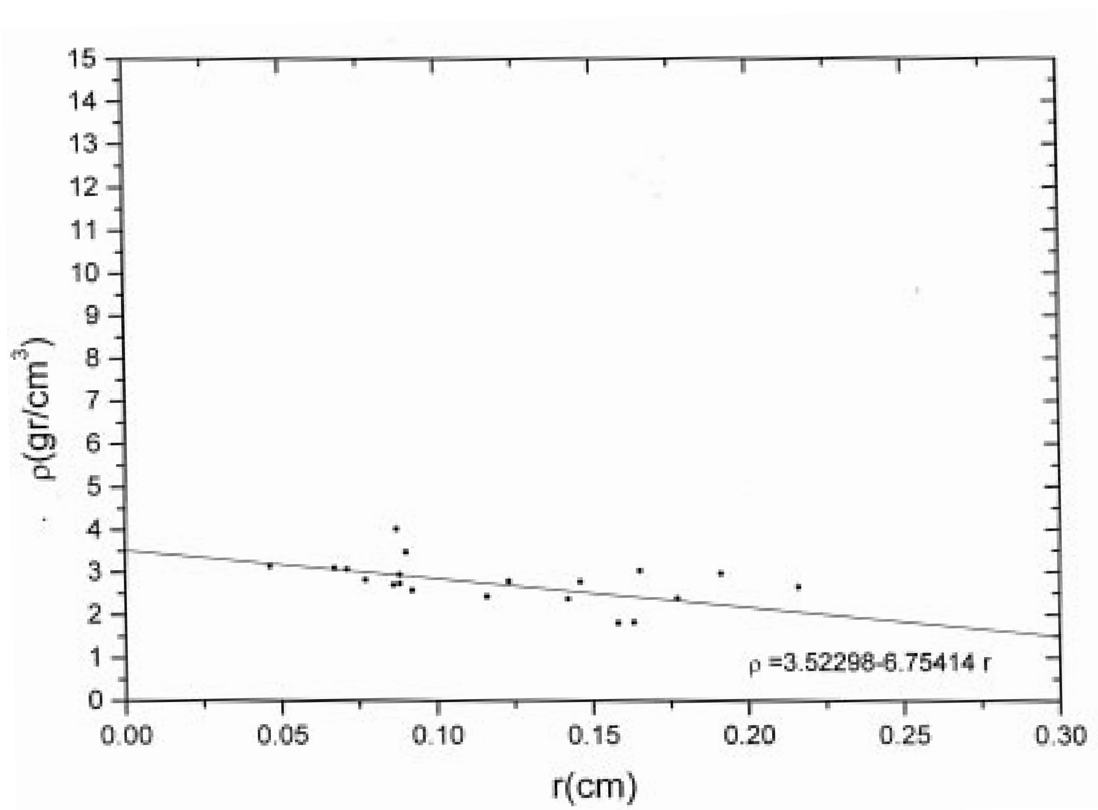


Fig. 4. Plot of density (ρ) of individual chondrules as a function of radius (r). The solid line corresponds to the least-square linear fit.

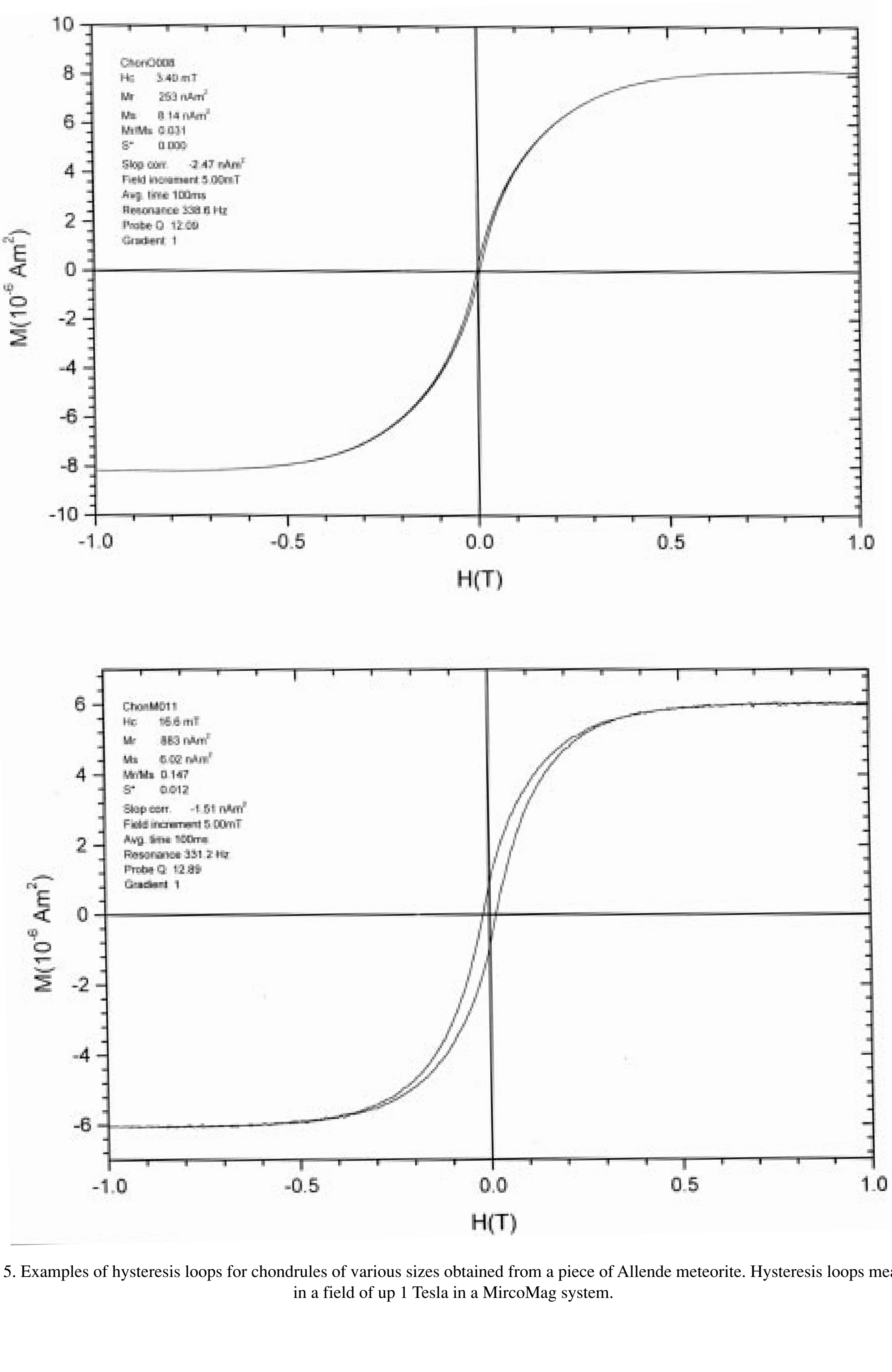
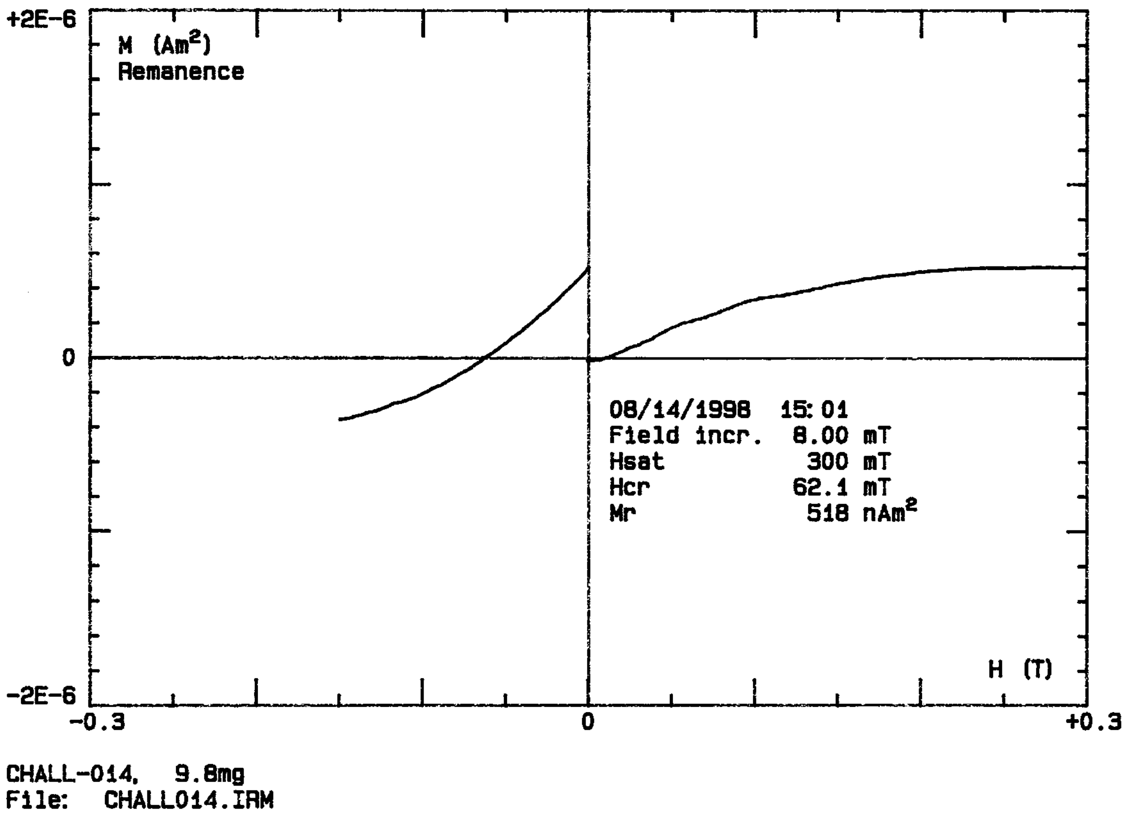


Fig. 5. Examples of hysteresis loops for chondrules of various sizes obtained from a piece of Allende meteorite. Hysteresis loops measured in a field of up 1 Tesla in a MircoMag system.



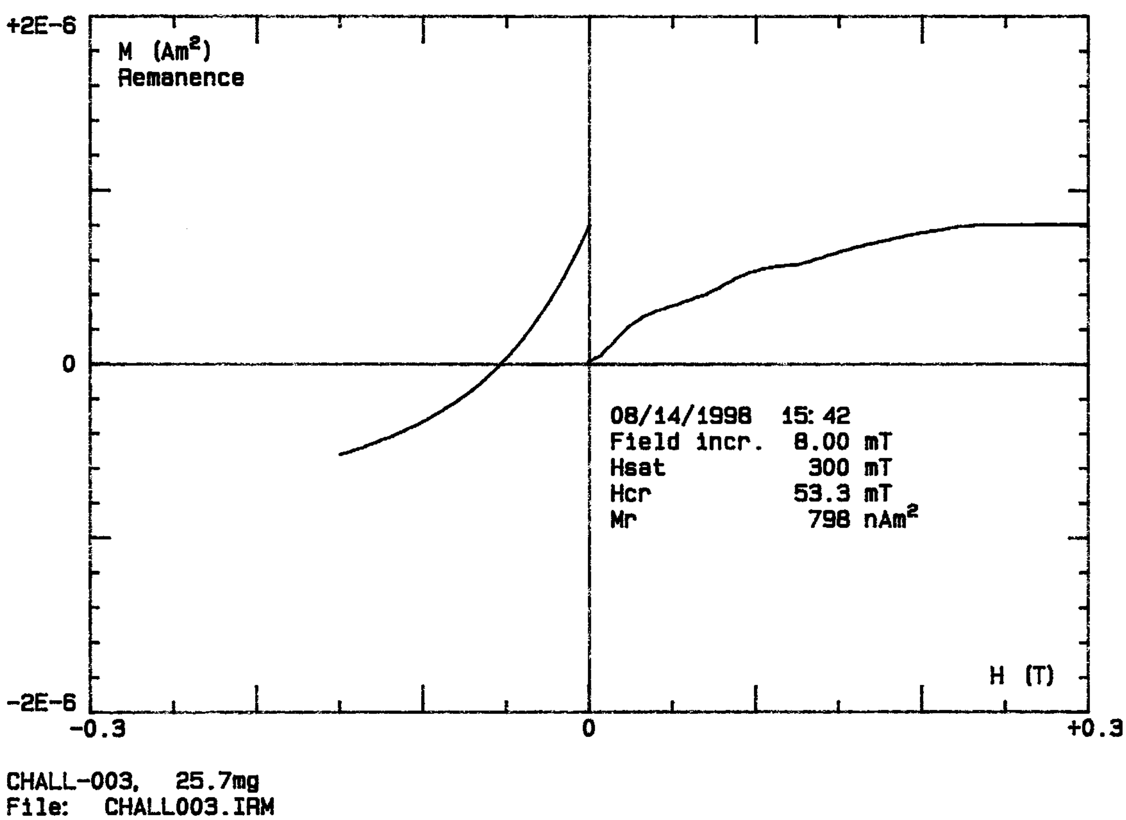


Fig. 6. Examples of isothermal remanent magnetization (IRM) acquisition curves and back-field demagnetization of saturation IRM for chondrules of various sizes obtained from a piece of Allende meteorite. Measurements carried out in the MicroMag system.

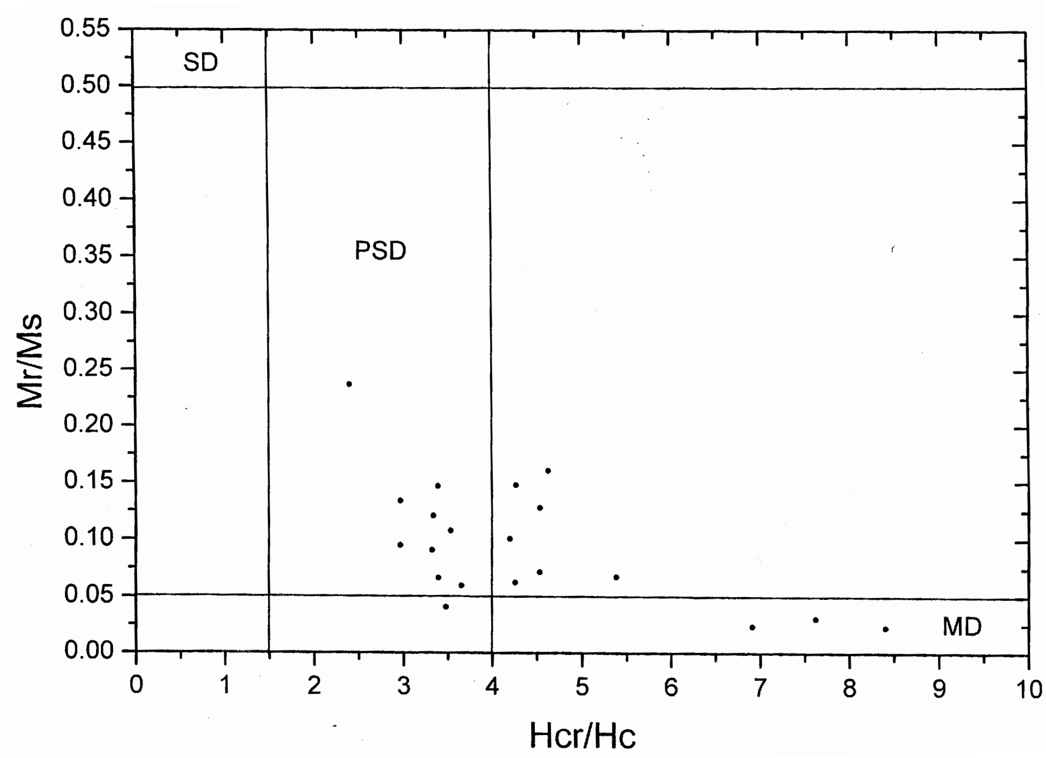


Fig. 7. Magnetization ratios (remanent/saturation magnetization, Mr/Ms) plotted as a function of the coercivity ratios (remanent/coercivity, Hcr/Hc). Hysteresis ratios plotted in a Day diagram (Day *et al.*, 1977) to characterize domain state of individual chondrules from the Allende meteorite. Data fall in the fields of pseudo-single domain (PSD) and multidomain (MD) states. No data fall in the single domain (SD) state.

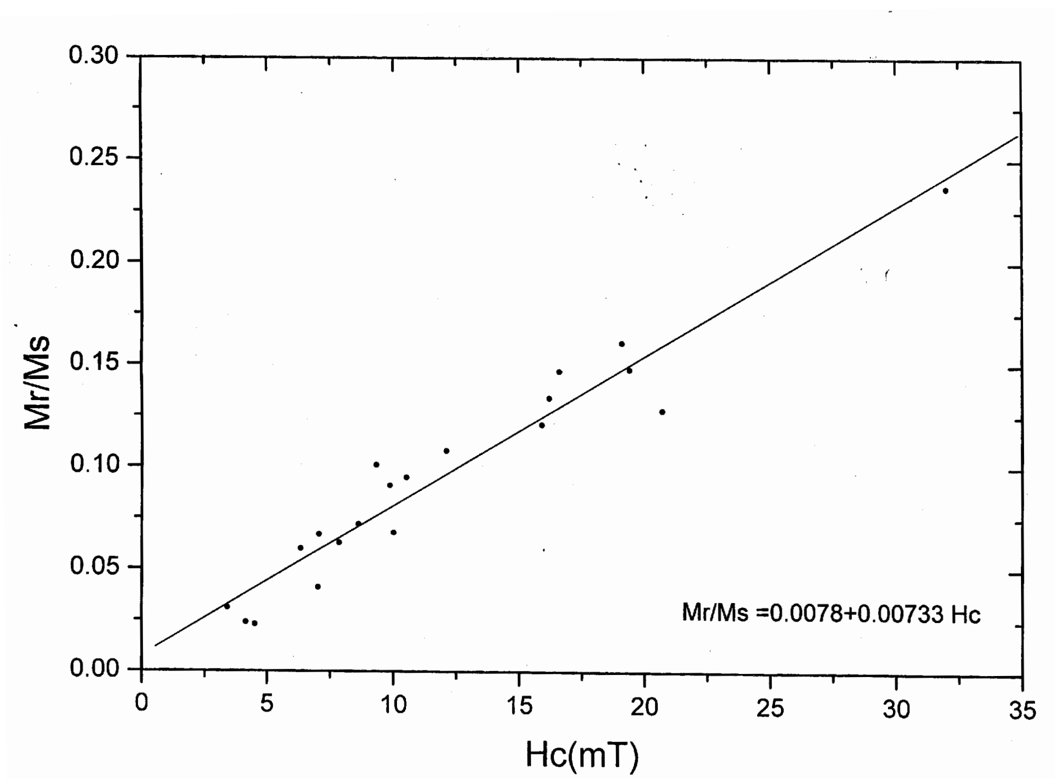


Fig. 8. Magnetization ratios (remanent/saturation, Mr/Ms) plotted as a function of coercivity (Hc). Three groups with characteristic coercitivity (Hc) values can be distinguished for further analysis: Group 1 for chondrules with Hc between 0 and 5 mT, group 2 for those with Hc between 5 and 15 mT, and group 3 for those with Hc larger than 15 mT. These groups correlate with other hysteresis parameters and the characteristic domain state (see Fig. 7).

In this project, a detailed study of the composition and structure of sensitive magnetic properties provides evidence on microstructural changes and temperature-dependent behavior of the remanent magnetization record of individual chondrules from the Allende samples. We report on hysteresis properties for a range of magnetic particle grain sizes and shapes with PSD and MD states, which can be related to other physical parameters in the individual chondrules. Further study of the magnetic mineralogy, including thermomagnetic properties, is needed to interpret the rock- magnetic data. If magnetite is the main mineral present in the chondrules, the data can be interpreted in terms of varying domain states, which may be separated into distinct groups.

In carbonaceous chondritic meteorites, magnetite has been found as the major magnetic mineral, and therefore proposed as the main remanence carrier (e.g., Sugiura and Strangway, 1988). Other iron minerals have been observed in chondritic meteorites. Among them, kamacite is a common mineral, and at small grain sizes its coercive force is high enough to contribute as a minor stable remanence carrier. Troilite has also been reported, though with its antiferromagnetic behavior it may not constitute a major remanence carrier. Kamacite usually shows low Hc and Mr/Ms ratios, being an unstable remanence carrier. In other types of meteorites, magnetite is not a common magnetic phase. This makes chondritic meteorites ideally suited for rock-magnetic studies, and at the same time for studies of the early magnetic fields in the solar system. Models for magnetite formation in the early solar nebula or in possible planetary bodies have been discussed in several studies (e.g., Kerridge *et al*., 1979; Choi *et al*., 1997; Hong and Fegley, 1998).

Studies of hysteresis properties have been used to investigate the nature of magnetic carriers and the magnetic stability of the paleomagnetic record. For instance, high values of Hc and Mr/Ms ratio imply high magnetic stability. Studies have documented wide ranges for these parameters in the different types of chondritic meteorites. Coercive force varies from less than 0.5 mT to almost 100 mT, and Mr/Ms varies from 0.001 to about 1 (Sugiura and Strangway, 1988). Differentiated meteorites present even wider variation ranges. Carbonaceous chondrites tend to show high Hc and Mr/Ms values. In this study, we observe a wide range in hysteresis properties for individual chondrules (Figures 7 and 8), which indicate different domain behaviors. Coercive force varies from about 0.5 mT to 25 mT (Figure 8). Mr/Ms ratios vary from about 0.001 to 0.22. If magnetite is the main magnetic mineral, then this variation in hysteresis parameters suggests a range of grain sizes (and shapes) corresponding to PSD and MD behaviors (Figure 7). The magnetization ratio Mr/Ms shows a tendency to increase as a function of coercive force Hc (Figure 8), which can be approximated by a linear relation. This relation has been early observed for the different types of chondrites and differentiated meteorites, with a wide range covering three orders of magnitude (Sugiura and Strangway, 1988). For homogenous assemblages of magnetic minerals, the magnetization ratio is proportional to coercivity (at low Hc ranges), and show saturation at higher Hc values. Sugiura and Strangway (1988) point out that the logarithmic-linear relationships observed for the different chondritic meteorite types may reflect mixing of kamacite and tetranite, plus grain size variations. In the differentiated meteorites, the SNC meteorites present the highest magnetization ratios and coercivity values. These high hysteresis parameters are associated with titanomagnetites, possibly due to magnetic domain subdivision of grains by ilmenite lamellae (Cisowski, 1986). In paleointensity studies, carbonaceous chondrites (with magnetite as a main magnetization carrier) and achondrites and SNC meteorites (with titanomagnetite as main magnetization carrier) have been currently considered to give the most reliable records. Nevertheless, a significant wide variation in paleomagnetic field intensities has been reported in the different studies. These discrepancies may be due to the complex magnetic mineralogy in meteorites and the magnetization acquisition mechanisms.

CONCLUSIONS

We examine individual chondrules from a fragment of the Allende meteorite, in contrast to bulk studies including matrix and chondrules. This has allowed us to document in detail the magnetic properties of individual chondrules. We find new relationships of sensitive magnetic parameters as a function of chondrule size. For instance, we have documented the dependence and variation of the remanent magnetization as a function of coercive force, where the ratio between the remanent and the saturation remanence (Mr/Ms) shows a rough linear tendency with coercive force Hc (Figure 8). This linear relation and the Hc range have been used to identify three distinct groups of chondrules with characteristic domain states and hysteresis properties. Three groups with characteristic coercitivities are distinguished: (a) group 1 for chondrules with Hc between 0 and 5 mT; (b) group 2 for those with Hc between 5 and 15 mT; and (c) group 3 for those with Hc larger than 15 mT. Group 1 chondrules plot within the MD field, group 2 chondrules plot in the PSD and intermediate fields with low Mr/Ms values, and group 3 chondrules plot in the PSD field with high Mr/Ms values. We have also found that the dominant domain state for individual chondrules falls within the multidomain state with coercivity ratios (remanence coercivity/coercivity; Hcr/Hc)) between 4 and 8 (Figure 7). Some small diameter chondrules presented pseudo-single domain states with Hcr/Hc ratios between about 3 and 4 (Figure 7).

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BIBLIOGRAPHY

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

BRECHER, A., 1972. Memory of early magnetic fields in carbonaceous chondrites. *In:* H. Reeves (Ed), Symposium on the Origin of the Solar System, Paris, CNRS, pp. 260-273.

CHOI, B. G., K. D. MCKEEGAN, L. A. LESHIN and J. T. WASSON, 1997. Origin of magnetite in oxidized CV chondrite: In situ measurement of oxygen isotope composition of Allende magnetite and olivine. *Earth Planet. Sci. Lett., 146,* 337-349.

CISOWSKI, S. M., 1986. Magnetic studies on Shergotty and other SNC meteorites. *Geochim. Cosmochim. Acta, 50,* 1043-1048.

CONNOLLY, Jr., H. C. and S. G. LOVE, 1998. The formation of chondrules: Petrologic tests of the shock wave model. *Science, 280,* 62-67.

DAY, R., M. D. FULLER and V. A. SCHMIDT, 1977. Hysteresis properties of titanomagnetites: grain size and compositional dependence. *Phys. Earth Planet. Inter., 13,* 260-267.

FLORES-GUTIÉRREZ, D. and J. URRUTIA-FUCUGAUCHI, 2000. Magnetic hysteresis properties and chondrule sizes in the Allende meteorite: Implications for heating/cooling conditions in the protoplanetary nebula. American Geophysical Union Fall Meeting, San Francisco, California, December 2000

HAGGERTY, S. E. and B. M. MCMAHON, 1979. Magnetite-sulfide-metal complexes in the Allende meteorite. Proc. 10th Lunar Science Conf., 851-870.

HEWINS, R. H., R. H. JONES and E. D. R. SCOTT (Eds), 1996. Chondrules and the Protoplanetary Disk. Cambridge Univ. Press, Cambridge, U.K.

HONG, Y. and B. FEGLEY, Jr., 1998. Experimental studies of magnetite formation in the solar nebula. *Meteor. Planet. Sci., 33,* 1101-1112.

KERRIDGE, J. F., A. L. MACKAY and W. V. BOYNTON, 1979. Magnetite in CI carbonaceous meteorites: Origin by aqueous activity on a planetesimal surface. *Science, 205,* 395-397.

KING, E. A. (Ed), 1983. Chondrules and their Origins. Lunar and Planetary Institute Publ., Houston Texas, USA.

KRING, D. A., 1991. High temperature rims around chondrules in primitive chondrites: evidence for fluctuating conditions in the solar nebula. *Earth Planet. Sci. Lett., 105,* 65-80.

LANOIX, M., D. W. STRANGWAY and G. W. PEARCE, 1978. The primordial magnetic field preserved in chondrules of the Allende meteorite. *Geophys. Res. Lett., 5,* 73-76.

MCSWEEN, H. Y., 1977. Chemical and petrographic constraints on the origin of chondrules and inclusions in carbonaceous chondrites. *Geochim. Cosmochim. Acta, 41,* 1843-1860.

MCSWEEN, H. Y., 1979. Ore carbonaceous chondrites primitive or processed? A review. *Rev. Geophys. Space Phys., 17,* 1059-1077.

NAGATA, T., 1979. Meteorite magnetism and the early solar system magnetic field. *Phys. Earth Planet. Inter., 20,* 324-341.

PRINZ, M., M. K. WEISBERG, C. E. NEHRU and J. S. DELANEY, 1986. Layered chondrules in carbonaceous chondrites. *Meteroitics, 21,* 485-486.

RUBIN, A. E., 1984. Coarse-grained chondrule rims in type 3 chondrites. *Geochim. Cosmochim. Acta, 48,* 1779-1789.

SUGIURA, N. and D. W. STRANGWAY, 1988. Magnetic studies of meteorites. *In:* J.F. Kerridge and M. S. Matthews (Eds), Meteorites and the Early Solar System, Arizona Press, p. 595-615.

SUGIURA, N., M. LANOIX and D. W. STRANGWAY, 1979. Magnetic fields in the solar nebula as recorded in chondrules from the Allende meteorite. *Phys. Earth Planet. Inter., 20,* 342-349.

URRUTIA-FUCUGAUCHI, J., 1980. Further reliability tests for determination of palaeointensities of the Earth's magnetic field. *Geophys. J. R. Astr. Soc., 61,* 243-251.

URRUTIA-FUCUGAUCHI, J., 1981. Some observations on short-term magnetic viscosity behaviour at room temperature. *Phys. Earth Planet. Inter., 26,* P1-P5.

WASILEWSKI, P., 1981. New magnetic results from Allende C3(V). *Phys. Earth Planet. Inter., 26,* 134-148.

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