PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Magnetism of Meteorites and Early Solar System Magnetic Fields [and Discussion]

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The magnetism of meteorites and early Solar System magnetic fields

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The characteristics of the remanent magnetization of chondrite, achondrite and shergottite, nakhlite and chassignite (SNC) meteorites are described, and interpretation in terms of magnetizing fields in the ancient Solar System discussed. The magnetism of ordinary chondrites is commonly scattered in direction within samples, implying magnetization of constituent fragments before accumulation. The magnetic history of these meteorites is uncertain because of lack of knowledge of the origin and properties of tetrataenite, an ordered FeNi alloy often carrying the bulk of the magnetization. Achondrites also often possess scattered magnetization, the primary component probably being acquired during cooling after differentiation of the parent body. A magnetizing field of internal origin is possible. Estimates of magnetizing field strength are in the approximate range 5–100 μT, with carbonaceous chondrites showing the highest values.

The SNC meteorites, probably originating on Mars, provide evidence for a weak, ancient Martian magnetic field of the order 1 μT.

1. Introduction

Almost all rocks possess a weak permanent magnetism (natural remanent magnetization (NRM)), contributed by a small content of magnetic minerals. In terrestrial rocks magnetite (Fe_3O_4), titanomagnetite ($x\mathrm{Fe_2TiO_4}\cdot(1-x)\mathrm{Fe_3O_4}$) and haematite ($\alpha$–$Fe_2O_3$) are of most importance, while iron and iron–nickel dominate in lunar rocks and meteorites. These magnetic minerals must undergo a process of magnetization before they and the rocks of which they form a part can acquire an NRM. In general, this requires that the mineral or rock experiences some event in the presence of a magnetic field. Examples of such events are the formation of magnetic minerals, heating and cooling, and severe shock. The resulting magnetization is generally very stable and can persist in the rocks for many millions or even billions of years. Also, the axis of the magnetization (or more precisely, the direction of NRM) is parallel to the magnetizing field direction at the site. Thus, these magnetized rocks contain a fossil record of the field and its direction at the site and time of the magnetizing event. It may also be possible to estimate the strength of the field. Investigation of the characteristics of the NRM potentially provides information on the event in which the NRM was acquired and its timing.

Palaeomagnetic studies of extraterrestrial materials are, of course, of more significance than simply the detection of ancient magnetic fields. The origin of the fields is of considerable interest, whether they are associated with the early

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solar nebula or Sun, or whether they are generated within a planetary or meteorite parent body by a dynamo process in a molten, electrically conducting core. The latter process is clearly of great significance regarding the structure and evolution of planets and asteroids and the existence of appropriate energy sources.

This paper surveys past and current research in the magnetism of meteorites and the evidence acquired regarding ancient magnetic fields in the Solar System. The magnetic properties of carbonaceous chondrites and iron meteorites are not considered here: in the latter any primary NRM is difficult to interpret because of large unstable secondary components which cannot easily be removed, and strong magnetic anisotropy, and little useful data have been derived from these meteorites (Brecher & Allbright 1977).

2. Ordinary chondrites

These chondrule-bearing, stony meteorites are the most common type, and their magnetism has been extensively studied. Their NRM is carried by nickel–iron particles of varying composition.

Early investigations of ordinary chondrites were carried out by Stacey *et al.* (1961), Gus'kova (1963), Brecher & Ranganayaki (1975), Sugiura (1977) and Brecher & Fuhrman (1979*a*) and Brecher *et al.* (1979). These studies revealed the presence of NRM in all samples, acquired before they impacted the Earth.

More recent studies revealed two important features of ordinary chondrite magnetization. The first is the widespread occurrence of tetrataenaite, the ordered, highly anisotropic and coercive iron–nickel mineral of approximately 50:50 composition (Clarke & Scott 1980; Nagata 1983; Wasilewski 1988). Although it is now known to contribute widely to chondrite NRM, its origin, evolution and process of magnetization are as yet incompletely understood. The second important feature is the occurrence of scattered directions of NRM within a meteorite sample. This phenomenon had already been observed between and within different physical phases, e.g. matrix and chondrules and between chondrules in Allende, but in ordinary chondrites it occurs not only as above but also between different regions of an apparently homogeneous matrix, sometimes on a scale down to about 1 mm (Funaki *et al.* 1981; Sugiura & Strangway 1982, 1983; Collinson 1987; Morden & Collinson 1992). This property of the NRM of ordinary chondrites is clearly of considerable significance in elucidating their magnetic history. It implies acquisition of NRM by meteoritic material before its assembly into the final parent body, with no subsequent magnetizing event. Such an event would result in a uniform, unidirectional NRM being imparted to the meteorite, or if, for example, severe metamorphic reheating occurred in the absence of an ambient field, then complete demagnetization would occur. Other aspects of this phenomenon are discussed further by Collinson (1992).

Another feature of the remanent magnetism of many meteorites of all types is the occurrence of secondary components of NRM. The primary NRM is the most stable and is acquired, for instance, through cooling from above the Curie point of the magnetic mineral(s) in an ambient magnetic field (TRM). Subsequently, if the material undergoes moderate heating or shock, or is exposed for an extended period to a magnetic field of constant direction, less stable components of magnetization can be acquired, namely partial TRM, shock magnetization (SRM) or viscous remanent magnetization (VRM) respectively. The most likely source of

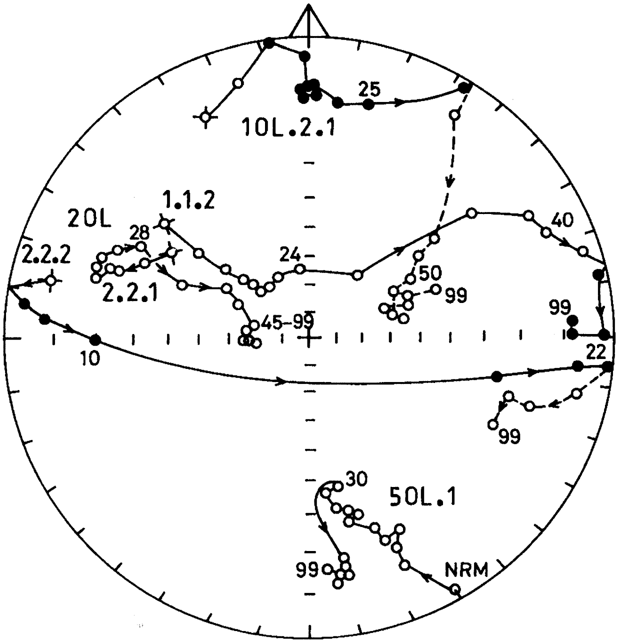

Figure 1. Stereogram of changes in NRM directions during alternating field demagnetization of Olivenza samples. Declination and inclination are referred to arbitrary axes and are measured clockwise round the circumference and from circumference to centre respectively. Starred circles are initial NRMs and numbers refer to demagnetizing fields. Full and open circles are directions in the upper and lower hemisphere, respectively. The three 20L subsamples are mutually oriented, and show the removal of a nearly uniform secondary magnetization and the presence of non-uniform primary NRM. 50L.1 shows only a small secondary component.

VRM is exposure to the geomagnetic field during the period between the fall of the meteorite and its discovery.

Secondary NRMs can usually be detected and removed by magnetic 'cleaning', using the techniques of alternating field and thermal demagnetization. Figure 1 shows examples of secondary NRM in the Olivenza LL5 chondrite. Evidence for the timing of secondary NRM acquisition can sometimes be obtained from the behaviour of NRM directions during demagnetization of mutually oriented subsamples of a meteorite. If the initial NRM directions of the subsample are uniform or cluster about a mean and diverge to different directions on demagnetization, then this implies acquisition of secondary magnetization after the meteoritic material was assembled into its final form. If initial subsample NRM directions are randomly distributed and each changes to further random directions on demagnetization, secondary magnetization of the subsample constituent fragments is implied.

3. Achondrites

(a) Howardites, eucrites and diogenites (HEDs)

These meteorites are of particular interest because they represent meteoritic material derived from a chemically differentiated parent body, and they may therefore record magnetic fields of internal, dynamo origin. The great majority

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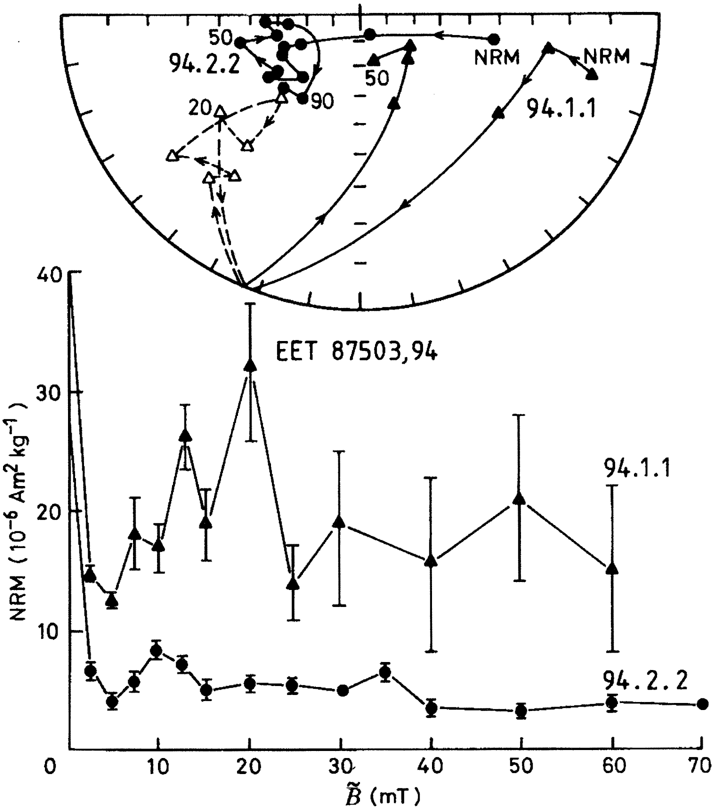

Figure 2. Anomalous AF demagnetization in achondrite EET 87503. Subsample 94.2.2 has a very soft secondary NRM removed in only 2.5 mT and a very stable primary component, and shows near normal behaviour. 94.1.1 shows highly anomalous decay of NRM intensity and irregular migration of NRM directions.

are monomict or polymict breccias, with some eucrites being unbrecciated. With few exceptions, the nickel–iron content of HEDs is low, usually in the range 0.1–1%, and kamacite is the important carrier of NRM.

In earlier studies (Brecher *et al.* 1977), scattered directions between subsamples were found in some meteorites, and Collinson & Morden (in press) have studied this phenomenon further. Of the ten HEDs studied, four howardites, a eucrite and a diogenite were heterogeneously magnetized, and another eucrite and diogenite were uniformly magnetized. Two diogenites were too weakly magnetized for unambiguous results. A common feature of the NRM of HEDs is its anomalous behaviour during alternating field demagnetization. In ‘normal’ behaviour, the NRM intensity decays steadily with increasing demagnetizing field. The NRM direction either remains essentially constant, or migrates systematically to another stable direction, according to the absence or presence of secondary NRMs. Figure 2 shows an example of this anomalous behaviour in the howardite EET 87503, highly irregular intensity variation, non-repeatable at the same demagnetizing field, and non-systematic variation in NRM direction, with no stable end point apparent.

Where anomalous demagnetization occurs, interpretation in terms of secondary magnetizations is very difficult. However, in many cases the mean intensity of

NRM decreases only slightly with increasing demagnetizing field, suggesting the presence of at least one stable NRM component. In other HEDs there is a quasi-systematic migration of NRM direction, although intensity changes are anomalous, and more than one NRM component is certainly present.

Other achondrites that have been studied are some ureilites (Brecher & Furhman 1979*b*) and the Estherville mesosiderite. The four ureilites investigated (Goalpara, Havero, Nova Urei and Kenna) are strongly magnetized, with kamacite as the dominant carrier. Where investigated, uniform NRM between subsamples was observed, with a stable NRM present and normal behaviour on demagnetization, significantly different results than those obtained by HEDs.

The Estherville stony-iron meteorite (mesosiderite) has similar remanent magnetic properties to the HEDs, i.e. heterogeneous NRM directions among matrix subsamples and the large nickel–iron fragments, anomalous AF demagnetization, and some evidence for both primary and secondary NRMs (Collinson 1991). Kamacite and tetrataenite are the important NRM carriers.

(*b*) *SNC meteorites*

One of the most interesting recent developments in meteorite studies has been the investigations of shergottite, nakhlite and chassignite (SNC) achondrites and the emergence of evidence that their parent body is Mars (McSween 1985). If these meteorites are of Martian origin, their petrological and physical (including magnetic) properties offer the opportunity of deriving evidence of Martian history and evolutionary events. Any remanent magnetism possessed by SNC meteorites may be evidence of the existence of a Martian magnetic field at the time when they experienced an event, e.g. heating and cooling or severe shock.

At the present time there are nine documented SNC meteorites, four shergottites, three nakhlites, one chassignite and one orthopyroxenite. Their NRMs lie in the range $(1\text{–}40) \times 10^{-6}$ Am^2 kg^{-1}, carried mainly by single and multidomain titanomagnetite. Alternating field demagnetization characteristics are variable, but directional stability is generally good, particularly in Shergotty (Cisowski 1986) and EETA 79001 (Collinson 1986). The NRM of one sample of ALHA 77005 is much less stable (Collinson 1986), but another sample possesses an NRM of greater stability (Nagata 1980). Chassigny is very weakly magnetized, but there are indications that it possesses a stable primary NRM. Nakhla and Zagami each possess stable primary and a secondary NRM (Collinson, unpublished data).

4. Palaeointensity determinations

In the process by which rocks acquire a remanent magnetization, the intensity of the resulting NRM is related to the strength of the magnetic field in which it was acquired. In principle, therefore, it is possible to determine the strength of the ancient field (palaeointensity) in which rocks were magnetized.

Although many palaeointensity determinations on meteorites have been reported in the literature (Cisowski 1987), it is necessary to regard them with some caution. The NRM of many meteorites is multi-component, secondary components are often difficult and sometimes impossible to remove, and primary NRM is often heterogeneous in direction within a sample. Tetrataenite commonly contributes to NRM in ordinary chondrites, and it is doubtful whether it possesses a simple TRM, and it is not possible to quantify the effect of shock on the NRM of meteorites.

In general these negative features have been ignored, but it might be hoped that over a sufficient number of determinations on different meteorites of the same type some statistically significant mean palaeointensities might be obtained.

Within the limitations of the measurements a broad difference in palaeointensities among different types of meteorite is suggested. Carbonaceous chondrites seem to have experienced a field of the order 100 μT, while achondrites, except the two ureilites, appear to have been magnetized in the fields of more than a magnitude weaker. SNC meteorites give a broad range of fields of approximately 0.4–4.0 μT. Probably the least reliable results are from the ordinary chondrites, and until the properties and origin of tetrataenite are understood and prior tests of NRM homogeneity carried out, more reliable results will be lacking.

5. Discussion

It is clear that the remanent magnetism of a wide range of meteorites confirms theoretical expectation that magnetic fields excited in the Solar System during the period covered by meteorite origin and during later events in their history. Four types of magnetic field may be considered. These are a compressed and amplified pre-planetary interstellar field, a field associated with the solar nebula when planetary material was condensing out of it, a field associated with the later Sun and fields generated within a meteorite parent body by some form of dynamo process. A different magnetization process may also be considered, namely the generation of transient magnetic field in the plasma produced during a collision in which there is sufficient energy interchange, and magnetization of material through shock or heating.

The remanent magnetism of meteorites arises from an event or events occurring in an ambient magnetic field. Since all meteorites constituents, with the exception of some phases in carbonaceous chondrites, have undergone moderate to severe heating at some stage, TRM must be the favoured process. Shock magnetization (SRM), acquired during impact shock, has been demonstrated in the laboratory (Cisowski *et al.* 1973; Srnka *et al.* 1979) but there are no unambiguous tests for identifying it in rocks or meteorites. Chemical remanent magnetization (CRM) can be acquired when a magnetic mineral is formed in a magnetic field. In meteorites, the formation of tetrataenite from the appropriate iron–nickel composition could possibly result in a form of CRM. Again, there is no test for identifying CRM.

If TRM is the dominant magnetizing process, an important feature of it is that cooling of the heated material down to ‘room’ temperature may take a time of typically days to thousands of years. During the cooling period the ambient field must be essentially constant in direction over the material. If a hot, rotating parent body is acquiring TRM in a spatially uniform magnetic field, only the field component parallel to the rotation axis will be effective in imparting TRM. On a longer timescale, orbital motion of the parent body could also result in averaging out of the field at points on its surface.

On the assumption that TRM is the primary magnetizing process, it is pertinent to enquire into the timing of the event. It is important here to consider the true meaning of ‘meteorite magnetization’. The widespread occurrence of heterogeneous NRM within meteorites indicates that they have not been magnetized after they have achieved their present form. What is being observed in this case is the sum of the magnetizations of different regions and/or phases within the samples. These can range from individual iron–nickel particles through chondrules and small aggregates of matrix and metal to larger matrix fragments and clasts. This is consistent with the common occurrence of brecciated meteorites, and suggests that primary magnetizations occurred on meteorite parent bodies before break up. There is also the possibility that iron–nickel grains were magnetized as they cooled in a magnetic field after condensation out of the solar nebula (Larimer 1978).

In many chondrites and achondrites there is evidence of secondary magnetizations, acquired before impact on Earth. The difficulties encountered with AF demagnetization often causes problems in interpreting the secondary NRMs, in particular the timing of the magnetizing event(s). Available evidence suggests that secondary NRM acquisition can occur before or after final accumulation, the process being either (or both) metamorphic heating and cooling or impact shock, possibly associated with lithification of brecciated meteorites (Kirsten 1978; Turner 1988).

For ordinary chondrites the evidence points to early primary magnetization of constituent material, either in the solar nebula or at the formation time of parent bodies and, where secondary NRM is present, later magnetization before final accumulation. The NRMs may be modified subsequently if production of tetrataenite continues after accumulation. The time of final lithification of brecciated meteorites and possible acquisition of secondary NRM is not generally known and is probably very variable. There is evidence that carbonaceous chondrites may have finally formed only about 2.5 Ma after parent body formation, whereas some ordinary chondrites record severe shock events as late as 1.4 Ga ago (Caffee & Macdougall 1988).

If TRM is generally the mode of acquisition of meteorite NRM, it is necessary for the magnetizing field to have a constant, or at least dominant direction during the cooling period, and the consequences of parent body rotation have already been noted. However, it is possible that most chondritic meteoritic material was magnetized in the form of small aggregates before their accumulation into a parent body, when cooling might be more rapid and the time required for a dominant field direction reduced.

The primary NRM possessed by HED achondrites is almost certainly a TRM acquired during cooling from the molten state during differentiation of the parent body. Subsequent repeated brecciation and ultimate lithification resulted in the observed heterogeneous NRM. Uniformly magnetized HEDs are either unbrecciated or they have undergone a remagnetization event. The relatively long cooling time of rotating parent bodies implies less likelihood of a steady magnetic field of external origin during TRM acquisition, and increases the possibility of a magnetizing field generated internally in a molten, electrically conducting core. This is discussed further below.

Although it is clear that magnetic fields were present during evolutionary events in meteorite history, clarification of their nature and origin from the NRM of meteorites remains elusive. Although much effort has been expended in measurements of palaeointensities, there are many factors which make for unreliable results. However, sufficient apparently reliable data have been acquired to indicate magnetizing fields in the approximate range 5–100 μT were present in the early Solar

System (Cisowski 1987). Information as to whether these fields were associated with the solar nebula, the early or later Sun or with the Sun passing through a T-Tauri stage is not currently available, because of lack of knowledge of the times of acquisition of NRM. Estimates of possible field strengths associated with dynamo action in the nebula (Levy & Sonett 1978), with induced currents in the nebula due to a solar magnetic field (Freeman 1977, 1978) and with a T-Tauri stage Sun (Levy & Sonett 1978) are in the required range. Hoyle (1960) had earlier estimated a nebula field of 100 μT as the agent for transferring angular momentum from the protosun to the separated ring of primitive planetary material.

The ability of small asteroid-sized bodies to support an internal dynamo-generated magnetic field remains uncertain, but the now strong evidence for an ancient lunar dynamo field (Collinson 1993) encourages the possibility. The basic requirements of a rapidly rotating electrically conducting core could have obtained in differentiated achondrite parent bodies, and it is tentatively proposed that the magnetizing field for the primary NRM of HED meteorites was of internal origin. The recent discovery by the Galileo spacecraft of a possible magnetic field associated with the S-type asteroid Gaspra may be relevant here (Kivelson *et al.* 1993).

The ubiquitous nature of remanent magnetism in meteorites and its independence of the extent of shock in them is evidence against magnetization in an impact-generated transient magnetic field or impact compression of a weak interplanetary field. There is also uncertainty concerning the viability of such processes. Theoretical work by Srnka (1977) and Hood & Vickery (1984) suggest the viability of field generation, and laboratory experiments by Srnka *et al.* (1979) and Crawford & Schultz (1988) show perturbation of an ambient magnetic field during hypervelocity projectile impacts, if not unambiguous field generation. Lunar magnetism provides no firm evidence for transient field magnetization being of major importance on the Moon (Collinson 1993), and currently it cannot be regarded as a serious candidate for meteorite magnetization.

6. SNC meteorites and the Martian magnetic field

The present Martian magnetic field is the subject of continuing controversy. Based on data obtained from the Russian Mars 2 and 3 (1971) and 5 (1974) orbiters and American Mariner 4 fly-by spacecraft, analyses have been presented for (Dolginov 1987) and against (Russell 1987) a present weak Martian magnetic field. The upper limit to any Martian dipole moment is approximately 2×10^{-16} Am^2, corresponding to an equatorial surface field of about 50 nT (Dolginov 1987). Additional data provided by the recent Phobos mission have not provided any further evidence for an intrinsic Martian field (Riedler *et al.* 1989). In the absence of firm data on the present Martian magnetic field, estimates of the strength of any ancient Martian magnetic field, based on the magnetism of SNC meteorites, is of considerable interest.

As mentioned in § 5, a rather wide range of palaeointensities has been derived from SNC samples, namely 0.4–4.0 μT. These fields are significantly larger than maximum values for the present field given by Dolginov (1987) and Russell (1987) of 0.1 and 0.01 μT respectively.

Two magnetizing processes may be proposed. A conventional process would be TRM acquired in an ambient field when the material cooled from a high temperature. An alternative possibility is magnetization by shock in an ambient field. Since SNC meteorites are likely to have been subjected to moderate or severe shock during ejection from the Martian surface, SRM cannot be ruled out. Shergotty and ALHA 77005 are believed to have been severely shocked about 180 Ma ago and later collisional events are suggested by exposure ages (McSween 1985). Nakhla shows no evidence of sufficient shock to impart SRM. Thermoremanent magnetization could certainly have occurred during cooling in an intrinsic Martian magnetic field at about 1.3 Ga ago, the radiometric age of the SNC meteorites. The interplanetary field is unlikely to have been as strong as indicated by the palaeointensity determinations (at least two orders of magnitude stronger than its present value). It is tentatively concluded that there was a significant global magnetic field on Mars at some time between 1.3 Ga ago and the present. Further work on existing SNC meteorites, and hopefully on future falls and finds, is needed before present indications, with their important implications for the Martian core and dynamo field generation, can be confirmed.

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Discussion

R. HIDE (*Oxford University, U.K.*). Could the passage of a shock wave through iron–nickel metal raise the temperature above the Curie point and allow the metal to be magnetized on cooling, but result in no apparent structural change in the metal?

R. HUTCHISON (*Mineralogy Department, Natural History Museum, London, U.K.*). 1. Shock in meteoritic metal induces phase transformation and changes in hardness, both of which are identifiable (see, for example, Buchwald 1975).

2. There is support for Dr Collinson's suggestion that eucrite and diogenite achondrites may have been magnetized by a core dynamo on the parent asteroid. These achondrites have the same oxygen isotopic ratios as the iron meteorites of chemical group IIIAB. This, the largest chemical group of irons, comprises members of which the trace element abundances vary systematically. It is concluded that these iron meteorites formed by the progressive crystallization of a core of molten iron–nickel, which is related to the eucrites, howardites and diogenites.

S. K. RUNCORN. The interpretation of the remanent magnetization of the most primitive bodies of the Solar System, the meteorites, has largely rested on the idea that the Solar System nebula had a strong magnetic field. Bodies cooling from a molten state, as the chondrules evidently did, would have been obtained a TRM from the component of the ambient field along their axes of spin. It is more difficult to imagine this happening to a large body such as Gaspra, because the much longer cooling time might have resulted, because of collisions, in it having no resultant magnetization. Consequently in the case of Gaspra, we are driven to the following scenario: magnetization by cooling in the early field of a planetary body. Accretion formed a small planet within about 1 Ma of the formation of the solar nebula and from nucleogenesis live ^{26}Al, of half-life 0.73 Ma, melts the body, resulting in the formation of an iron core. The recent discovery of evidence for ^{60}Fe, which has a half-life of 1.4 Ma, in the early Solar System provides a heat source to generate motions in the liquid core. A dipole magnetic field, on average aligned along the axis of spin of the parent body, would be constant in direction with respect to any piece of the silicate mantle. But the proto-asteroid must cool down from above the Curie point to low temperature while the field is present. For this reason, and because the proto-asteroid must be knocked out of the parent body, it must be near the surface. The reasonably rapid cooling might result from the sudden removal by a collision of the blanket of dust, usually seen on asteroids. The thermal history of the parent body would have had to have been special and the conclusion follows that not every asteroid will be found to have uniform magnetization.

Additional references

Buchwald, V. F. 1975 *Handbook of iron meteorites*, pp. 125–136. Berkeley: Universities of California and Arizona State.