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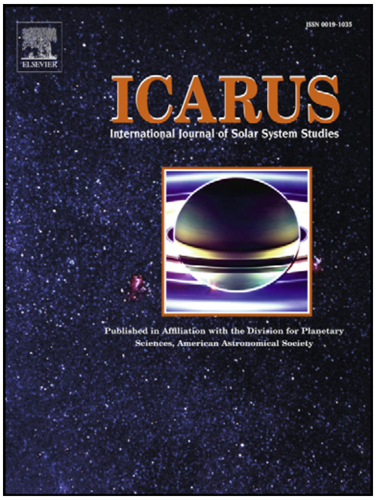

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Low-temperature magnetic properties of iron-bearing sulfides and their contribution to magnetism of cometary bodies

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Running head: Low temperature cometary magnetism

Abstract

In this study we present a review of low-temperature magnetic properties of alabandite (Fe,Mn)S, daubreelite $FeCr_2S_4$ pyrrhotite $Fe_{1-x}S$ and troilite FeS updated with new experimental data. The results indicate that besides FeNi alloys mainly daubreelite with its Curie temperature T_C ~150 K and strong induced and remanent magnetizations may be a significant magnetic mineral in cold environments and may complement that of FeNi or even dominate magnetic properties of sulfide rich bodies at temperatures below T_C.

Comets are known to contain iron bearing sulfides within dusty fraction and their surfaces are subject to temperature variations in the range of 100-200 K down to the depth of several meters while the cometary interior is thermally stable at several tens of Kelvin which is within the temperature range where alabandite, daubreelite or troilite are "magnetic". Thus not only FeNi alloys, but also sulfides have to be considered in the interpretation of magnetic data from cometary objects such as will be delivered by Rosetta mission. Modeling indicates that magnetic interactions between cometary nucleus containing iron-bearing sulfides and interplanetary magnetic field would be difficult, but not impossible, to detect from orbit. Rosetta's Philae lander present on the surface would provide more reliable signal.

Keywords

Comets, Magnetic fields, Meteorites

Introduction

Iron nickel (FeNi) alloys are dominant magnetic phase in most achondritic and chondritic meteorites and lunar samples (Rochette et al. 2003, 2008, 2009). Review of the magnetic properties of FeNi system can be found for example in Wasilewski (1974).

Additionally, carbides, phosphides and sulfides can be found in some achondritic and chondritic or martian meteorites (Rochette et al. 2003, 2008, 2009). While most of these sulfides (with the exception of ferrimagnetic monoclinic pyrrhotite $Fe_{1-x}S$) are antiferromagnetic or paramagnetic at room temperature, various magnetic transitions occur at lower temperatures enhancing their induced or remanent magnetization, or both. In this study we provide a review of low-temperature magnetic data available for alabandite (Fe,Mn)S, daubreelite $FeCr_2S_4$ pyrrhotite $Fe_{1-x}S$ and troilite FeS and present additional experimental results on these materials.

Such a review is useful for understanding of the magnetic properties of primitive extraterrestrial materials at low temperatures typical for their original environment. Possible applications of these data include modeling of the interaction of extraterrestrial bodies with interplanetary magnetic fields in different temperature ranges. For example ESA (European Space Agency) Rosetta mission (launched in 2004) is due to arrive to comet 67P/Churyumov-Gerasimenko in May 2014 and conduct observations during the approach the comet to the Sun (Glassmeier et al. 2007a). Both orbiter and Philae cometary lander are equipped with magnetometers (Rosetta Plasma Consortium Magnetometer (RPC-MAG) and Rosetta Magnetometer and Plasma Monitor (ROMAP) respectively). Preliminary studies (Auster et al. 2007, Glassmeier et al. 2007) take into account only FeNi alloys as the magnetic mineral present in cometary material.

Most stony meteorites and related asteroidal parent bodies are more abundant in FeNi metallic phase than in the iron bearing sulfide phase. Thus FeNi metal will dominate their magnetic properties (with certain sulfides as daubreelite being significant contributor). In contrast, iron bearing sulfide phase seems to be more abundant in cometary dust.

Iron, bearing sulfides (mainly troilite, pyrrhotite and FeNi sulfide pentlandite) have been reported in interplanetary dust particles (IDP's) (Dai and Bradley 2001, Rietmeijer 2005) and in cometary dust (Brownlee et al. 2006, Lisse et al. 2006, Zolensky et al. 2006). Moreover, sulfides in these extraterrestrial materials are volumetrically more abundant than a FeNi metallic phase. For this reason the magnetic properties of these sulfides must be considered when interpreting magnetic observations of cometary bodies. Additionally, we consider alabandite and daubreelite as potential compounds present within dusty fraction in our modeling.

Instruments and Methods

The magnetic measurements were done at the Institute for Rock Magnetism, University of Minnesota (IRM) using Quantum Designs MPMS-5S cryogenic susceptometer (AC/DC). In a previous study (Kohout et al. 2007) the FC (Field Cooled) and ZFC (Zero Field Cooled) induced (in 10 mT field) magnetization curves were shown to be most suitable for the detection of iron bearing sulfides, particularly daubreelite. Thus, we measured FC and ZFC curves on warming from 5 K to 300 K in 5 K steps for 14 additional enstatite meteorite samples.

The chemical composition of sulfides present in meteorite samples was determined at Czech Geological Survey, Prague, Czech Republic (CGS) using CamScan3200 scanning electron microscope (SEM) equipped with Microspec WDX 3PC Wavelength-dispersive spectrometry

(WDS) analyzer. The analyses were performed using an accelerating voltage of 20 kV, 24 nA beam current, 1 μm beam size and ZAF correction procedures. The counting time was 30 s for all analyzed elements. The instrument was calibrated using a combination of natural and synthetic standards.

Iron bearing sulfides in extraterrestrial material

Alabandite

Alabandite (Fe,Mn)S is a naturally occurring mineral that crystallizes in isometric hexoctahedral (face centered cubic – f.c.c.) NaCl structure. Magnetic properties of synthetic alabandite are summarized in Heikens et al. (1977). Alabandite is paramagnetic at room temperatures and orders antiferromagnetically below the Néel temperature of T_N ~ 148 K. At T_{tr} ~ 130 K a phase transition occurs interpreted as an abrupt inversion of the rhombohedral distortion of the f.c.c. lattice along [111] plane accompanied by discontinuous change in the magnetic susceptibility as observed on single crystals.

The magnetic susceptibility and induced magnetization in 10 mT field of antiferromagnetic MnS below T_N remains low, in the range of ~ 10^{-7} m^3/kg and ~ 0.003-0.004 Am^2/kg, respectively. However, iron free MnS samples slightly enriched in Mn compared to ideal composition show antiferro to ferrimagnetic transition at T_T ~ 50 K accompanied with sharp one to two orders of magnitude increase in induced magnetization on cooling through this transition (Petrakovskii et al. 2001).

The substitution of Mn ions by Fe has a pronounced effect on the Néel temperature which increases with increasing iron content up to T_N ~ 185 K for the $Fe_xMn_{1-x}S$ system of x=0.2 (Petrakovskii et al. 2002). Moreover, according to Loseva et al. (1998) and Petrakovskii et al.

(2002), samples with higher Fe content (x > 0.25) exhibit ferrimagnetic behavior above room temperature with Curie temperatures T_C from 730 K (x ~ 0.27) to 860 K (x ~ 0.38). However, the magnetization of this ferrimagnetic phase is weak, close to that of paramagnetic MnS.

Troilite

Troilite is an iron sulfide with an ideal stoichiometric composition FeS. It crystallizes into a peculiar lattice (space group $P\bar{6}2c$), which can be thought of as being derived from the NiAs structure. The troilite supercell axes are $a = \sqrt{3}A$ and $c = 2C$, where A and C are NiAs subcell axes (Hägg and Sucksdorff, 1933). Magnetic properties of troilite above room temperature have been studied extensively (Haraldsen 1937, 1941, Hirahara and Murakami 1958, Murakami and Hirahara,1958, Murakami, 1959, Schwarz and Vaughan 1972, Horwood et al. 1976, Li and Franzen 1996). Between room temperature and Neél temperature of ~ 600 K (~ 325°C) troilite is antiferromagnetic, with spins parallel to the *C*-axis of the NiAs subcell below ca. 445 K (Horwood et al. 1976) and orthogonal to it at higher temperatures up to the Neél point at T_N ~ 600 K. The low temperature data measured on troilite powderized fraction extracted from the Bruderheim L6 chondrite reveal an existence of a magnetic transition at T_T ~ 70 K (Kohout et al. 2007). The nature of this transition is not well understood and is a subject of ongoing research. The magnetic susceptibility remains low at ~ 10^{-7} m^3/kg below the transition with one order of magnitude sharp peak at the transition temperature. The induced magnetization in 10 mT field though increases sharply below the transition, but remains low in the range of ~ 0.1-0.3 Am^2/kg.

Pyrrhotite

Pyrrhotite $Fe_{1-x}S$ is an iron sulfide with iron deficiency compared to troilite. Two forms are commonly found in natural samples. While at the room temperature the hexagonal pyrrhotite of stoichiometric compositions Fe_9S_{10} and $Fe_{11}S_{12}$ is antiferromagnetic, the monoclinic form Fe_7S_8 is ferrimagnetic and thus contributes significantly to the bulk rock magnetic properties. Based on the review by Dunlop and Özdemir (1997) the hexagonal pyrrhotite becomes ferrimagnetic in the narrow temperature range between ~ 475 K (~ 200°C) and ~ 540 K (~ 265°C). The Curie point of monoclinic pyrrhotite is higher at ~ 595 K (~ 320°C). The magnetic susceptibility and the saturation remanent magnetization of monoclinic pyrrhotite at room temperature vary with the grain size in range of 1000-7000 10^{-8} m^3/kg and 2-6 Am^2/kg respectively (Dekkers,1988). The monoclinic pyrrhotite has a low-temperature transition in remanence and coercive force at 30-35 K (most likely isotropic point of the magnetocrystalline anisotropy, Dekkers 1989, Rochette et al. 1990, Dunlop and Özdemir 1997).

Daubreelite

Daubreelite ($FeCr_2S_4$) is a naturally occurring mineral that crystallizes in the cubic spinel lattice, Fe^{2+} occupying tetrahedral and Cr^{3+} octahedral sites. Below the Curie temperature T_C ~ 150 K Fe^{2+} and Cr^{3+} spins are antiparallel, their inequality producing an overall ferrimagnetic order. Magnetic properties of the natural daubreelite from Coahuila IIAB hexaedrite iron meteorite and of the synthetic $FeCr_2S_4$ are summarized by Kohout et al. (2007) and Tsurkan et al. (2001a,b,c), respectively.

The magnetic susceptibility and induced magnetization in 10 mT are relatively high, in the range of ~ 10^{-4} m^3/kg and ~ 3.5-5 Am^2/kg, respectively. From the published data, a magnetic transition can be identified as a local magnetization maximum at T_m ~ 60 K (Tsurkan et al. 2001a,b,c). Cooling through this transition is accompanied by spin-glass-like features and cubic-to-triclinic symmetry reduction within crystallographic domains (Tsurkan et al. 2001a,b,c, Maurer et al. 2003, Müller et al. 2006).

Variations of T_m and T_C in daubreelite-bearing meteorites

In order to get deeper insight into the variation of T_m and T_C in daubreelite we measured FC and ZFC induced magnetization curves of 14 additional enstatite chondrites covering both enstatite subgroups (EH and EL) and all petrographic types (3-6). Most of these meteorites contain natural daubreelite of various amounts and compositions and thus are suitable natural source of daubreelite for our studies.

The meteorites come from three different collections. Antarctic finds ALH 81 021 (EL6), EET 96 341 (EH4-5), KLE 98 300 (EH3) and MAC 88 136 (EL3) were provided by NASA Johnson Space Center, USA. Meteorites Abee (EH4), Blithfield (EL6), Hvittis (EL6), Indarch (EH4, S4) and Pillistfer (EL6) were provided by the Geological Museum, University of Helsinki, Finland. Meteorites Adhi Khot (Kot) (EH4), Daniel's Kuil (EL6), Jajh Deh Kot Lalu (EL6), St. Mark's (EH5) and Saint-Sauveur (EH5) were provided by Natural History Museum, London. The data of the Neuschwanstein meteorite are from Kohout et al. (2007). The meteorites are listed in Table 1.

A strong contribution of daubreelite to the FC and ZFC induced magnetization is apparent in all EL chondrites while it is weak or missing in EH chondrites (Fig. 1). The kamacite and iron bearing sulfide abundances and daubreelite compositions were subsequently evaluated on thin sections using SEM-WDS and the results were evaluated with aim to find the relation between the daubreelite compositions and shift in its T_m and T_C temperatures.

From the results of enstatite meteorites it is apparent that the daubreelite in all samples contain 0.83-3.25 wt% Mn^{2+} replacing Fe^{2+} ions. However, no obvious correlation was observed between average Mn^{2+} content in daubreelite within the meteorites and variations in its T_m or T_C temperatures (Table 2). Additionally, there was no correlation observed between the homogeneity of daubreelite and enstatite subgroup, petrographic type, or shock level. However, it is apparent that daubreelites in all enstatite meteorites have systematically lower T_C by up to 20 K and higher T_m by ~ 10-15 K, compared to pure synthetic material. Also the natural daubreelite from the Coahuila iron meteorite (with no significant impurities detected) has T_m higher by ~ 10 K, but T_C close to that of synthetic material.

It seems likely that presence of Mn in daubreelite decreases its T_C. There might be also an increasing effect on T_m. However, this is not supported by Coahuila daubreelite sample. An alternative interpretation (Tsurkan et al. 2001b) explains variations in T_m or T_C temperatures in daubreelite in terms of stress or lattice distortions. With existing data we can’t draw a definite conclusion.

Discussion

In the Table 3 we compare magnetic susceptibility, induced magnetization and saturation remanent magnetization of alabandite, daubreelite, monoclinic pyrrhotite and troilite to that of FeNi metal (20 wt% of Ni). We are aware of the fact that the actual values might depend on mineral grain size or composition (i.e. Ni concentration) and thus we present the values as order of magnitude estimates of multi-domain (MD) particles. From the table III it is apparent that magnetization of alabandite or troilite in certain temperature regions is still one to three orders of magnitude lower compared to that of FeNi. However, the magnetization values of daubreelite are of the same order of magnitude as those of FeNi. This explains the fact that despite a roughly equal abundance of all of the above mentioned sulfides and kamacite in enstatite chondrites, contributions of daubreelite and kamacite only are apparent in the FC and ZFC induced magnetization curves while signatures of alabandite and troilite are too weak to be detected.

Based on empirical observations as well as on theoretical models (Spencer et al 1989, Lim et al 2005), the present surface temperatures of NEAs (Near Earth Asteroids) and asteroids within the main asteroid belt are above temperatures where alabandite, daubreelite or troilite show significant magnetism.

However, modeling of comet 46P/Wirtanen (Heubner et al. 2006 pp. 197-198) or 67P/Churyumov-Gerasimenko (Heubner et al. 2006 p. 199) shows that the cometary surface is subject to temperature variations in the range of 100-200 K down to the depth of several meters while the cometary interior is thermally stable at several tens Kelvin. This is within the temperature range where alabandite, daubreelite, or troilite are also “magnetic”. Thus not only FeNi alloys, but also sulfides have to be considered in the interpretation of magnetic data from cometary objects such as will be delivered by Rosetta mission.

Furthermore, the approach of the comet towards the Sun and the rotation of its nuclei will cause variations in the surface temperature. This may produce detectable changes in the magnetic properties of the comet as various sulfides will change their magnetic ordering states at their characteristic transition temperatures.

To demonstrate and compare magnetic properties of these minerals present within extraterrestrial materials let us model a cold icy cometary body containing dispersed 10 wt% fine-powder fraction of alabandite, daubreelite, monoclinic pyrrhotite, troilite or FeNi metal. As the magnetic susceptibility of such a body is proportional to the concentration of the magnetic minerals we can estimate from Table 3 the magnetic susceptibility of such a body to be ~ 10^{-8} m^3/kg in the case of either alabandite or troilite (Fig. 2). This is below the magnetic susceptibility of most meteorites (only some HED or SNC meteorites have such low values).

Presence of 10 wt% of monoclinic pyrrhotite will result in susceptibility comparable to these materials while 10 wt% of daubreelite will result in a magnetic susceptibility ~ 1000 x 10^{-8} m^3/kg which is comparable to most carbonaceous or LL and L ordinary chondrites or aubrite or ureilite achondrites. Thus, such a cometary body will show similar magnitude of interactions with IMF (Interplanetary Magnetic Field) as with parent bodies of these meteorites. A comet with 10 wt% of finely dispersed FeNi metal would produce still by an order of magnitude higher induced magnetization. As mentioned earlier the magnetic susceptibility of an extraterrestrial body is proportional to the concentration of the magnetic minerals and will vary with the real abundance of those minerals and their mixtures.

The estimate of induced magnetization measured by space probe orbiting a minor solar system body is discussed in Kohout et al. (2008). This modeling reveals that it will be difficult, but not impossible, to detect such interactions orbit. Based on Eq. 11 in Kohout et al. (2008), the induced magnetization measured on the orbit around a comet containing 10 wt% of finely dispersed daubreelite in 10 nT IMF will be in range of 10^{-1}-10^{0} nT. This is within the resolution limit of Rosetta's RPC-MAG instrument (31 pT, Glassmeier et al.2007b). The ROMAP instrument on the Philae lander (resolution 10 pT, Auster et al. 2007) should provide stronger signal and might detect those interactions more reliably.

As the cometary activity increases on its approach to the Sun, dust and volatiles are released to form a coma surrounding the nucleus. Complex solar wind interactions with dust and ionized gas within the coma are expected. Also here a dusty magnetic mineral fraction may contribute to the solar wind driven magnetic interactions. However, it is difficult to quantitatively predict the scale of these interactions.

The magnetic remanence of small dusty grains was recognized as an important factor in the aggregation process (Dominik and Nübolt 2002, Nübolt et al. 2003) and may lead to accretional remanence of cometary bodies (Nübolt and Glassmeier 2000). However, such a remanence does not need to be preserved till present time.

Any extraterrestrial body remanence carried by iron bearing sulfides will be erased while the material warms-up through described sulfide magnetic transitions (Kohout et al. 2007). This can happen periodically to the outer layers of the minor solar system bodies during their orbital or rotational history (asteroids or periodical comets). Due to this the remanence carried by most iron bearing sulfides (with exception of monoclinic pyrrhotite) may be partly lost.

The magnetic remanence carried by FeNi grains or monoclinic pyrrhotite may be more stable. While the MD particles are susceptible to viscous magnetic effects, the small SD (single-domain) grains may carry remanent magnetization over a long time and may be carriers of cometary remanent magnetization.

Conclusions

Besides FeNi alloys mainly monoclinic pyrrhotite and daubreelite below its T_C ~150 K with strong induced and remanent magnetizations may be a significant magnetic minerals in cold environment. In the case of daubreelite strong induced magnetization below 150 K may complement that of FeNi or even dominate magnetic properties of sulfide rich bodies at these temperatures.

Additionally iron free alabandite samples slightly enriched in Mn compared to ideal composition show antiferro to ferrimagnetic transition at T_T ~ 50 K accompanied with accompanied with sharp one to two orders of magnitude increase in induced magnetization on cooling.

Similar behavior is observed in troilite where magnetic susceptibility shows one order of magnitude sharp peak and induced magnetization increases sharply (but remains low in the range of ~ 0.1-0.3 Am^2/kg) below a transition at T_T ~ 70 K.

Our model of a cometary body with 10 wt% of alabandite or troilite dusty fraction reveals magnetic interactions an order of magnitude lower than that of the HED or SNC achondritic materials while 10 wt% of monoclinic pyrrhotite is already within this range. Presence of 10 wt% of daubreelite results in a magnetic interaction similar to these of aubrite, carbonaceous, L, LL or ureilite meteorite parent bodies and 10 wt% of FeNi metal produces still an order of magnitude higher induced magnetization. Magnetic interactions between comets containing iron-bearing sulfides and IMF will be difficult, but not impossible, to detect from orbit. The lander present on the surface should provide more reliable signal.

Cometary interiors are kept cold at temperatures at several tens Kelvin while the approach of the comet towards the Sun and the rotation of its nuclei will cause variations in the surface temperature. This may produce detectable changes in the magnetic properties of the comet as various sulfides will change their magnetic ordering states at their characteristic transition temperatures. In future work, other sulfides common in extraterrestrial materials (i.e. pentlandite $(Fe,Ni)_9S_8$) should be magnetically characterized at low temperatures.

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Tables

Table I. List of meteorites subjected to the magnetic measurements.

Meteorite	Group and type	Fall/Find	Shock level
Abee	EH4	FA 1953	S2-5
Adhi Khot	EH4	FA 1919	S4
ALH 81 021	EL6	FI	S2
Blithfield	EL6	FA 1910	S2
Daniel's Kuil	EL6	FA 1868	S2
EET 96 341	EH4-5	FI	
Hvittis	EL6	FA 1901	S2
Indarch	EH4	FA 1891	S4
Jajh Deh Kot Lalu	EL6	FA 1926	S2
KLE 98 300	EH3	FI	
MAC 88 136	EL3	FI	S3
Neuschwanstein	EL6	FA 2002	S2
Pillistfer	EL6	FA 1868	S2
Saint-Sauveur	EH5	FA 1914	S4
St. Mark's	EH5	FA 1903	S3

Table II. Magnetic transition (T_m) and Curie (T_C) temperature of daubreelite within enstatite chondrites and daubreelite elemental composition. Included are also data for daubreelite from Coahuila IIAB hexaedrite (Kohout et al. 2007) and for synthetic daubreelite (Tsurkan et al. 2001a).

Meteorite	Group and type	T_m (K)	T_C (K)	Daubreelite composition		
				Mn abundance range (wt%)	Mn average abundance (wt%)	Structural formula (atoms per four sulfur formula unit)
Abee	EH4	-	-			
Adhi Khot	EH4	-	-			
ALH 81 021	EL6	69	153	2.63-2.80	2.73	$(Fe_{0.875-0.880}Mn_{0.138-0.148})_{1.018-1.022}Cr_{2.031-2.032}S_4$
Blithfield	EL6	80	155	1.58-2.61	2.20	$(Fe_{0.862-0.920}Mn_{0.083-0.138})_{1.000-1.002}Cr_{1.997-2.010}S_4$
Daniel's Kuil	EL6	72	155	2.23-2.89	2.57	$(Fe_{0.850-0.886}Mn_{0.116-0.152})_{1.011-1.021}Cr_{2.022-2.025}S_4$
EET 96 341	EH4-5	65	156			
Hvittis	EL6	81	160	2.52-2.61	2.56	$(Fe_{0.876-0.883}Mn_{0.135-0.138})_{1.014-1.018}Cr_{2.012-2.023}S_4$
Indarch	EH4	74	148	2.35-2.97	2.64	$(Fe_{0.845-0.873}Mn_{0.124-0.157})_{0.998-1.002}Cr_{2.014-2.018}S_4$
Jajh Deh Kot Lalu	EL6	69	154	1.74-2.86	2.41	$(Fe_{0.864-0.909}Mn_{0.091-0.150})_{1.001-1.014}Cr_{1.980-1.997}S_4$
KLE 98 300	EH3	-	-			
MAC 88 136	EL3	78	148	0.83-2.81	1.84	$(Fe_{0.862-0.974}Mn_{0.044-0.148})_{1.010-1.018}Cr_{2.017-2.028}S_4$

Neuschwanstein	EL6	71	155	2.09-3.25	2.89	$(Fe_{0.803-0.878}Mn_{0.125-0.198})_{1.001-1.003}Cr_{2.008-2.012}S_4$
Pillistfer	EL6	71	156	0.53-2.11	1.52	$(Fe_{0.892-0.976}Mn_{0.028-0.111})_{1.003-1.004}Cr_{1.998-2.018}S_4$
Saint-Sauveur	EH5	-	-			
St. Mark's	EH5	76	155			
Coahuila	Iron	76	164			
synt. daubreelite		~ 60	167			

Table III. The magnetic properties of the sulfides considered in this study. Data are from Dekkers, 1988, Kohout et al. 2007, Petrakovskii et al. 2001, 2002, Tsurkan et al. 2001a,b,c, and Heikens et al. 1977.

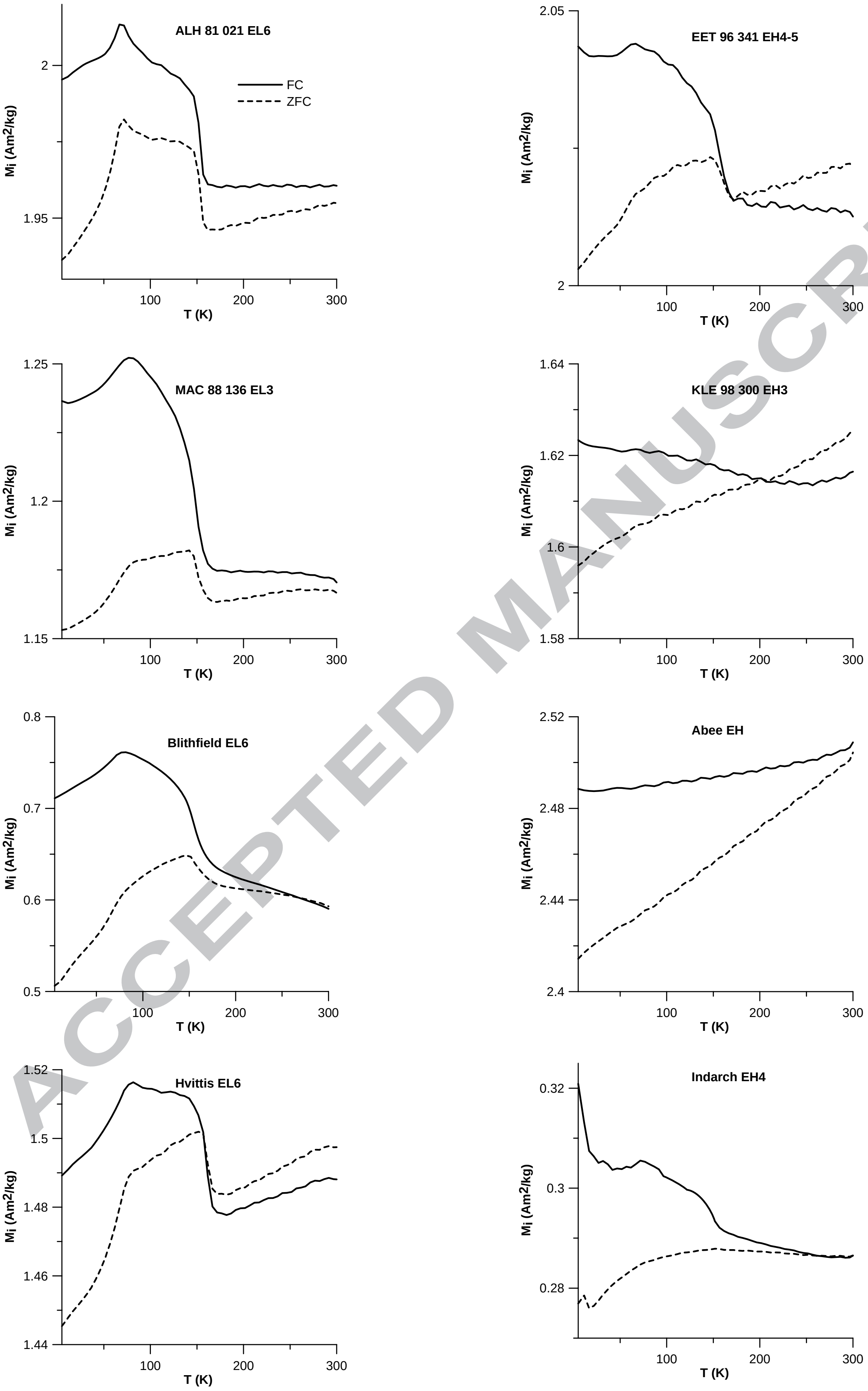
Magnetic mineral	Magnetic susceptibility $(10^{-8}\ m^3/kg)$	Induced magnetization in 10 mT field (Am^2/kg)	Saturation remanence imprinted by 1 T (Am^2/kg)
Alabandite (below 150 K)	10	0.003-0.004 0.01-0.1 (below 50 K for MnS slightly enriched in Mn)	
Daubreelite (below 165 K)	10000	3.5-5	~ 4-12
Troilite(below 70 K)	10	0.1-0.3	~ 0.3
Pyrhottite	1000		2-6-
FeNi metal (20 wt% of Ni)	100000	~ 10	~ 2-3

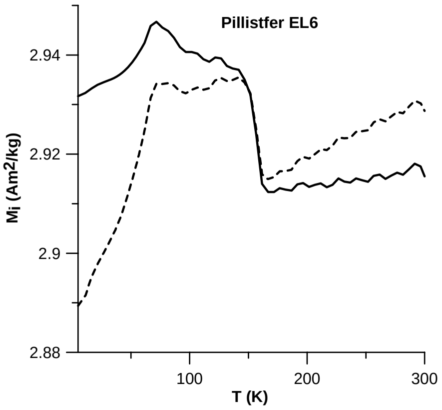
Figure captions

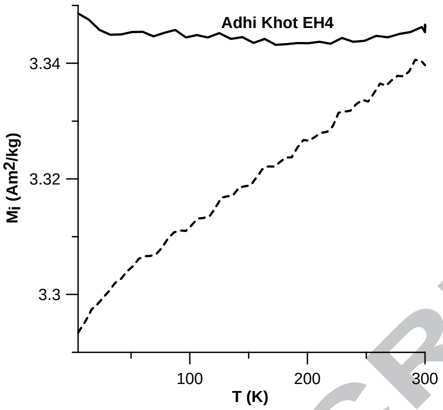
Figure 1. Field cooled (FC) and Zero Field Cooled (ZFC) induced (in 10 mT field) magnetization curves of 15 enstatite meteorites.

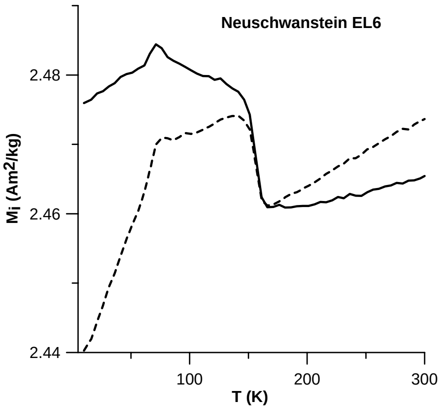
Figure 2. Model magnetic susceptibility of an icy comet containing dispersed 10 wt% fine-powder fraction of alabandite, daubreelite, troilite or FeNi metal and its comparison to susceptibility of meteorites. The temperature of the cometary body with sulfides is supposed to be within the temperature interval specified in table III. Meteorite data are from Rochette et al. (2003, 2008, 2009).

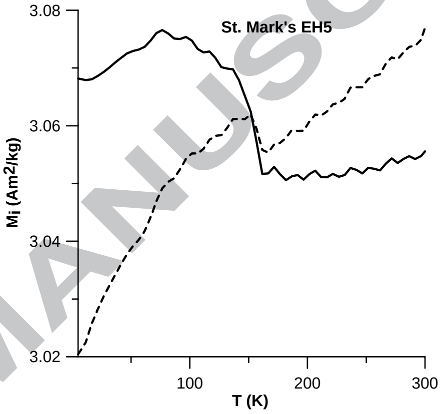
Fig 1

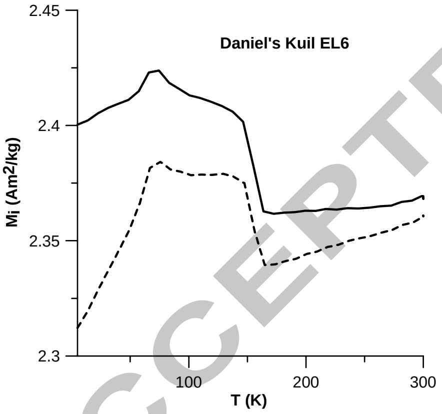

ALH 81 021 EL6
FC
ZFC
2
1.95
EET 96 341 EH4-5
2.05
2
MAC 88 136 EL3
1.25
1.2
1.15
KLE 98 300 EH3
1.64
1.62
1.6
1.58
Blithfield EL6
0.8
0.7
0.6
0.5
Abee EH
2.52
2.48
2.44
2.4
Hvittis EL6
1.52
1.5
1.48
1.46
1.44
Indarch EH4
0.32
0.3
0.28
Mi (Am2/kg)
100
200
300
T (K)

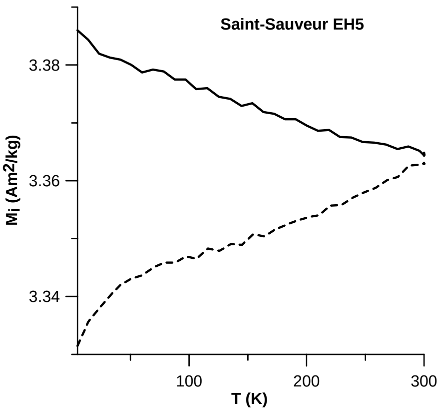

Pillistfer EL6
2.94
2.92
2.9
2.88
Mi (Am2/kg)
100
200
300
T (K)


Adhi Khot EH4
3.34
3.32
3.3
Mi (Am2/kg)
100
200
300
T (K)


Neuschwanstein EL6
2.48
2.46
2.44
Mi (Am2/kg)
100
200
300
T (K)


St. Mark's EH5
3.08
3.06
3.04
3.02
Mi (Am2/kg)
100
200
300
T (K)


Daniel's Kuil EL6
2.45
2.4
2.35
2.3
Mi (Am2/kg)
100
200
300
T (K)


Saint-Sauveur EH5
3.38
3.36
3.34
Mi (Am2/kg)
100
200
300
T (K)

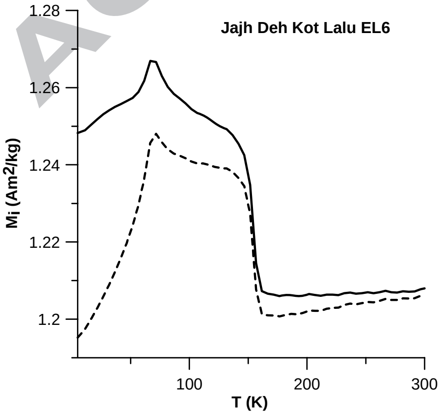

Jajh Deh Kot Lalu EL6
1.28
1.26
1.24
1.22
1.2
Mi (Am2/kg)
100
200
300
T (K)

Fig 2


Log χ 10⁻⁸ (m³/kg)
0
1
2
3
4
5
comet with 10 wt% of alabandite
comet with 10 wt% of troilite
comet with 10 wt% of pyrrhotite
comet with 10 wt% of daubreelite
comet with 10 wt% of FeNi
Ureilites
Acapulcoites-Lodranites
Winonaites
Angrites
Aubrites
Brachinites
SNC (high)
SNC (low)
Diogenites
Eucrites
Howardites
Mesosiderites
R
K
LL
L
H
E
CM
CV
C2
CO3
CK
CI
C3-4
CR
CH
CB