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A possible assessment of an origin of remanent magnetism of the Fermo H-chondrite breccia: a study of diffusion of heat from the surface of the meteorite into its interior

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Abstract. Fermo meteorite, who fell on September 25, 1996 (Molin et al. 1997) is analysed from the viewpoint of its remanent magnetization (RM) and a simplified model describing heating of a meteoroid is discussed. The main carrier of RM of the H3-5 Fermo chondrite, according to Curie temperature and the results of thermal demagnetization of samples, is probably the taenite (γ phase). The results have approved that the intensity and the directional stability (declination and inclination) of RM of Fermo disappeared completely at 500-600°C. A solution of mathematical model for penetration of temperature inside a spherical meteoroid heated from its surface has shown that there exists some time interval in which the sphere in almost of half of its radius was heated to the temperature above or close to the Curie temperature of taenite ($T_C \approx$ 560-600°C). This means that when the meteoroid becomes so hot (500-600°C) any eventual extraterrestrial magnetization cannot survive and completely disappears. A new RM probably of thermoremanent (TRM) origin was induced by the geomagnetic field after fall of the meteorite on the Earth's surface.

Key words: meteorite – H3-5 Fermo chondrite – taenite – thermoremanent magnetization – mathematical model

1. Introduction

Fermo is a stony meteorite which fell down on September 25, 1996 at 15:30 UT in central Italy about 3-4 km from the town of Fermo and near the Adriatic coast. The meteorite was recovered as a single stone of the weight of 10.2 kg, within a crater about 30-40 cm and about 200 m away from the nearest farm house. The meteorite is classified as an ordinary chondrite breccia H3-5 (Molin et al. 1997).

Orlický et al. (2000) have proposed that the dominant magnetism carrier in the Fermo chondrite is the taenite and that the natural remanent magnetization (NRM) of the meteorite is supposed to be of thermoremanent (TRM) origin. Kamacite is also present in the meteorite, but it is not able to acquire and carry the TRM due to its transformation at high temperatures. Originally, Orlický et al., 2000 applied only two small pieces for the study of the Fermo meteorite. Not enough samples were available for further experiments at the beginning of the previous study of the meteorite. As we have known, very questionable problem is a source and origin of the NRM of the Fermo meteorite. We have interested if the remanent magnetism of the meteorite was obtained either within the extraterrestrial or terrestrial magnetic fields. For this reason we have extended our investigation and studied additional samples of Fermo which kindly granted us Prof E. Fedeli, the Mayor of the town Fermo.

First we present an outline of some conceptions about possible magnetizations of meteorites:

- the necessary field may have been associated with the solar nebula during the early stages of formation of the solar system (Stacey, 1969). Such a field requires a parent body with a large metallic core still liquid, which could be a source of the field, while the chondritic mantle was cooled enough to have acquired remanence. The experiences do not prove such behaviour of chondrites.
- shock magnetization (SRM) is a possible source of remanence for meteorites (Wasilewski 1976, 1977; Nagata et al. 1983), particularly those showing mineralogical evidence of one or more shock events. However, a presence of an ambient field seems necessary if a SRM of significant magnitude is to be obtained. Reduction of pre-existing NRM through shock demagnetization is more likely, particularly in recent shock events. In any case rapid cooling of taenite, as would be likely to follow shock heating, may produce martensite, a crystal which is a distorted form of alpha Ni-Fe that is metastable, particularly at high temperatures. Martensite is capable to carry the remanence, so the role of martensite in the remanent magnetization of shocked meteorites is important (Wasilewski 1974). Moreover Ni-poor specimens display thin oriented lines of shock origin, called Neumann lines, within their kamacite groundmass.
- static uniaxial stress can also impart a remanent magnetization (called piezoremanent magnetization - PRM) to meteorites if applied in the presence of ambient field (Nagata et al. 1982).
- according to Guskova and Pochtarev (1967) all meteorites originated in a core-mantle differentiated planetary body, capable of sustaining core-dynamo magnetic fields of 0.4–0.9 Oe.
- Brecher and Albright (1977) presented an opinion that e.g. in iron meteorites all magnetization directions (NRM, TRM and spontaneous magnetization - SM) in octahedrites appear to be preferentially associated with the oc-

tahedral gamma crystalographic planes on which alpha plates nucleated and grew, and/or aligned with their intersections. They proposed that the laboratory TRM can align with an external magnetic field direction only if the field lies in or close to an octahedral plane. According to these authors the strong and stable magnetization of iron meteorites may conceivably be merely spontaneous ferromagnetism, which has been directionally stabilized along and in energetically favourable easy axes and planes defined crystalographically, through a combination of magnetocrystalline anisotropy and phase anisotropy of the kamacite needles and plates. These preferred directions may not necessarily be coherent on a large scale, so that asteroidal chunks of meteoritic iron may not be uniformly magnetized. However, the finer the metalographic structure, the stronger, stabler and more coherent the NRM seems to become.

According to Cisowski (see Jacobs 1987, Vol.2, Chapter 6) many ordinary chondrites, along with carbonaceous chondrites had the potential for recording information about magnetic fields in the early solar system and many others would have been magnetically reset in much later times. Many of ordinary chondrites may actually be monomict or polymict fragmental breccias that formed after their peak metamorphism (Scott et al. 1985). So, an original NRM of these breccias was probably removed during metamorphism. We know that the Fermo meteorite has been classified as an H3-5 genomictic chondrite breccia (Molin et al. 1997). So, it would be more difficult to reveal if the TRM, or chemical remanent magnetization (CRM) of the meteorite was obtained in the presence of an extraterestrial field or a terrestrial one. According to Lovering et al., 1960, it is important to note that the central portion of a meteorite of more than about 6 cm in diameter is not appreciably heated by its fly through the atmosphere. Ablation of the surface keeps pace with the inward diffusion of heat, leaving only a 3 cm heated skin. So far, an idea about a possible magnetization of a meteorite during its flight through the atmosphere or after its fall on the earth's surface, has been very rarely considered. Magnetization by the geomagnetic field during a flight of a meteorite through the atmosphere requires that the body or a meteoroid may not rotate around any of its axis during the flight. The second very important condition is temperature, which should be closely over the blocking temperature of the magnetism carrier of the meteorite. Magnetization by the geomagnetic field after a fall of the meteorite on the earth's surface requires that the temperature of the meteorite will not be less than of about 550-570°C (what is the Curie temperature of the taenite, which is the dominant carrier of NRM of Fermo). This provoked us to formulate our first version of a mathematical model to compute the diffusion of the heat from the surface of the meteorite to its interior, during its flight through the atmosphere and successive fall on the earth's surface. We have added so far obtained knowledge on new magnetic parameters to present more complex view about the potential source of remanent magnetization of the meteorite.

2. Experimental works and results

Five irregular pieces were cutted from a larger sample of Fermo and distances of individual samples from its top to the central parts together with their determined parameters (weigh, volume, densities and basic magnetic characteristics) are summarized in Table 1. The sample 1 contains also fusion crust. Thermal diffusivity ($\varkappa$) of one sample was determined by T. Šrámková in the Institute of Physics, Slovak Academy of Sciences, Bratislava. The purpose of the density

Table 1. Basic data of the samples

Sample	Distance (mm)	Weight (g)	Volume (cm^3)	Density (kg/dm^3)	$\kappa \times 10^3 (m^3/kg)$ SI Units	NRM$\times 10^2$ (Am^2/kg)	Q
1	2.0	0.5183	0.141	3.67	190.657	35.906	4.2
2	8.5	1.3936	0.405	3.44	156.668	11.174	1.6
3	17.5	1.3890	0.402	3.45	158.890	22.448	3.2
4	25.0	0.7075	0.195	3.63	190.636	57.559	6.7
5	42.0	5.4943	1.600	3.43	193.200	22.700	2.5

determination was to assess if concentration of metallic phase is homogeneous. We see that the density of the samples 2, 3, 5 are very similar, while the samples 1 and 4 have appeared to have higher densities. The average density is of $\sigma =$ 3.516 kg/dm^3. The individual samples differ slightly in magnetic susceptibility (κ), but there are extreme differences in the intensities of normal remanent magnetization (NRM) among individual samples. While the values of κ have pointed out that there are not very different concentrations in metallic Fe-Ni minerals, NRM of the samples has been induced inhomogeneously within the meteorite. We suppose that there is a higher concentration of the taenite within the sample 4 (with the highest intensity of NRM), except of more distinctly confined Ni-Fe grains within the groundmass, comparing it with those detected by ore microscopy in the sample 2 (with the lowest intensity of NRM).

In order to have a more complex view we have included into our analysis also the values of κ and NRM of two pieces of Fermo presented by Orlický et al. (2000) and designated here as Fermo-1 and Fermo-2. The values of magnetic susceptibility and NRM after their recalculation to 1 g are very close to those presented in Table 1 (Fermo-1: $\kappa = 175.0 \times 10^{-3}$, NRM=14.579 $\times 10^{-2} Am^2/kg$; Koenigsberger ratio Q=1.9; Fermo-2: κ =131.358 x 10^{-3}, NRM=12.904 $\times 10^{-2}$-Am^2/kg; Q=2.19). The sample 5 which is from the central part of the meteorite was thermally demagnetized within a magnetic vacuum (Fig.1). We see from Fig.1 that the intensity of NRM disappeared completely at 600°C. The directional (declination and inclination) stability of the NRM is up to 550°C. Similarly like in previous results (Orlický et al. 2000) the carrier of RM, according

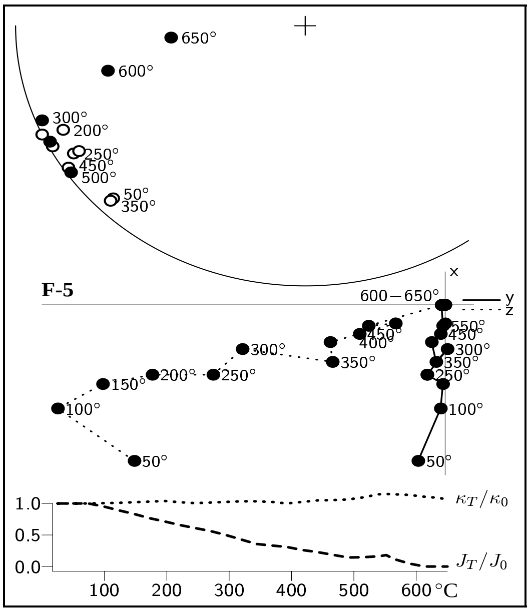

Figure 1. Thermal demagnetization of sample F-5, stepwise heating to 650°C; Zijderveld diagrams and stereographic projection of the remanent magnetization (RM); *full circles* - positive, *open circles* - negative RM (in stereographic projection); κ_T, κ_0 – magnetic susceptibility at T and at 25°C, respectively; J_T, J_0 – remanent magnetization at T and at 25°C, respectively.

to Curie temperature measurements and the thermal demagnetization results of the additional samples of the Fermo meteorite, is probably the taenite.

Two samples were subjected to the Thellier method to study a paleointensity of Fermo. We see from Fig.2 that while the demagnetization of NRM of both samples does follow quite well in the whole applied interval from 25–550°C, an acquisition of partial thermoremanent magnetization (PTRM) in the laboratory field has not obeyed the Thellier's rule in the interval of 25 to cca 350–400°C. It appears that the Thellier method is acceptable only within the interval of 450–550°C for our samples. Different values of the coefficient $k(k = \Delta\text{NRM}/\Delta\text{PTRM}$; see Fig.3) were obtained for investigated samples (k_1 = 1.97 and k_2= 1.17 for the sample 1 and 2, respectively), with an average value of $(k_1 + k_2)/2 = 1.57$. When we consider the intensity of the laboratory field of H = 0.0485 mT, the paleointensity computed for Fermo meteorite is of about F = 0.0752 mT.

We have also applied the results from the previous analysis (Orlický et al. 2000) and compared the values of NRM of Fermo-1 and Fermo-2 with the values

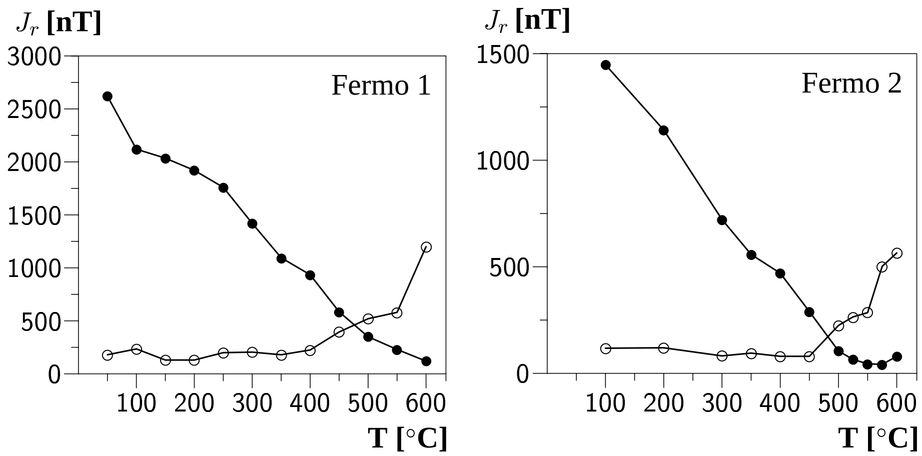

Figure 2. Thellier method, demagnetization (*full circles*) and magnetization (*open circles*) curves of both Fermo 1 and Fermo 2 samples. (J_r - remanent magnetization in nano Tesla (nT) with respect to temperature T).

of PTRM which were obtained at 550°C in the laboratory field of the intensity 0.0485 mT for the same samples (Fermo-1: NRM = 14.579×10^{-2}Am^2/kg;, PTRM = 15.404×10^{-2}Am^2/kg; Fermo-2: NRM = 12.904×10^{-2}Am^2/kg; PTRM = 13.172×10^{-2}Am^2/kg). Fermo-1: NRM/PTRM = 0.947; Fermo-2: NRM/-PTRM = 0.980. A comparison of these data results in an idea that the NRM of the Fermo meteorite was induced in a magnetic field of the paleointensity near F = 0.0467 mT, what is of course different of that F = 0.0752 mT derived by other method. We are not able to prefer any value of the above paleointensities of the field in which the Fermo meteorite was induced.

We have taken into account the fact that both ways of determination of paleointensity have had some methodical difficulties. One of them is a transformation of troilite (FeS) to magnetite during laboratory heating of Fermo on air. Troilite is present in Fermo, except of taenite, plessite and kamacite (Orlický et al. 2000). The transformation of troilite is actual at the temperatures over 400°C due to thermal dissociation of sulphur and successive substitution by oxygen (if present). The Fe oxide, mostly nonstoichiometric Fe_3O_4 with strong ferrimagnetic properties is created instead of original Fe-sulphide. Curie temperature of the magnetite $T_C \approx 580$°C is very near of that of taenite. It means that we are not able to differ taenite from magnetite on the base of the Curie temperature measurements. But very perfect detection of magnetite is based on the so called Verwey transition temperature T_V (at about -150°C for stoichionometric magnetite; the value of T_V depends on purity of the crystalline lattice of magnetite) by measurements of a change of magnetic susceptibility during cooling of the

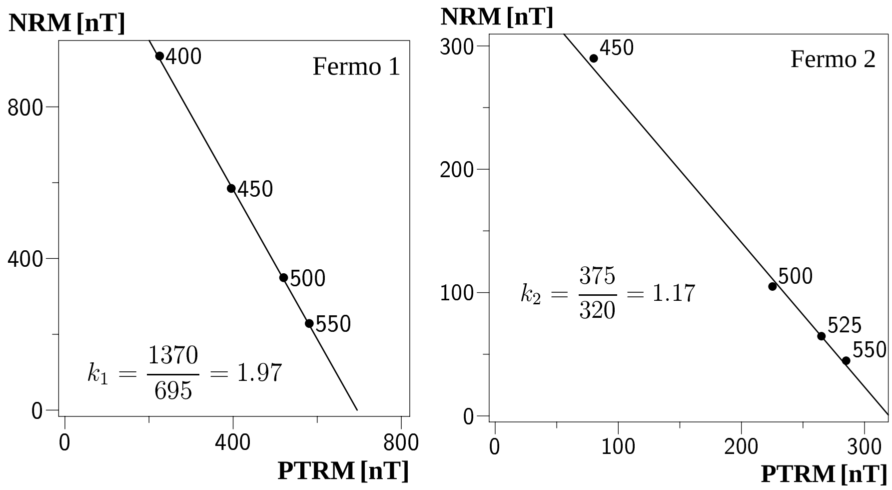

Figure 3. Graphical illustration of data NRM/PTRM for computation of coefficients k_1 (Fermo 1), k_2 (Fermo 2). NRM – natural remanent magnetization; PTRM – partial thermoremanent magnetization of the samples.

sample from laboratory temperature down to liquid nitrogen temperature. We applied this method to measure the samples of Fermo-1 and Fermo-2, which were previously heated on air during Thellier method (Fig.2). The T_V corresponds to about -132°C for both samples. It means that the nonstoichiometric magnetite was created during thermal treatment of samples (Fig.4). But this magnetite acquired also the PTRM except of the taenite in the laboratory field. So it influenced the total PTRM as well as computed paleointensity of Fermo samples.

3. Mathematical model for penetration of temperature inside a spherical meteoroid heated from its surface

A meteoroid during its flight through the atmosphere is surrounded by a hot plasma the temperature of which is about 10^3 K (Ceplecha et al., 1998). Regardless of the short time of flight in the atmosphere (up to about 10 s) it is doubtless that this thermal shock can penetrate into interior of the meteoroid also after an ablation stage. A mathematical model for the heating process after ablation can be derived on the basis of solution of the heat conduction equation in the spherical co-ordinate system. The temperature $U(r,t)$ is function of the radius r and time t, and represents change of the temperature from the initial temperature of the sphere outside the atmosphere. This equation is well known

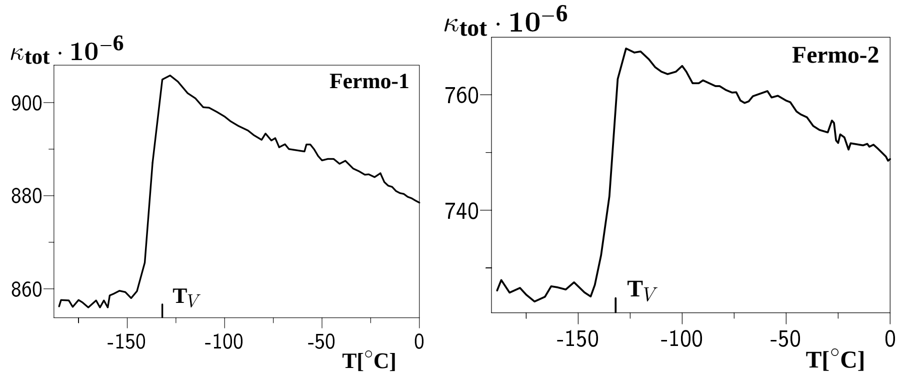

Figure 4. The detection of the Verwey transition temperature (T_V) of nonstoichiometric magnetite in Fermo samples. The measurements of the change of magnetic susceptibility (κ) of samples within the 0°C and - 190°C.

(Carslaw and Jaeger, 1959) and is given as:

$$r^{-2}\frac{\partial}{\partial r}\left(r^2\frac{\partial U}{\partial r}\right)=\frac{1}{\varkappa}\frac{\partial U}{\partial t} \tag{1}$$

where $\varkappa=\lambda/(\rho c_p)$. The coefficient λ is the heat conductivity, ρ is the density and c_p is the specific heat of the material of the meteoroid (sphere). The initial temperature $U(r,0)$ is zero. The process of the heat exchange on the surface of the sphere is described by the boundary condition on its surface $r=a$,

$$\lambda\left(\frac{\partial U}{\partial r}\right)_{r=a}+H(U-T_g(t))|_{r=a}=0,\quad \text{i.e.}\ \left(\frac{\partial U}{\partial r}\right)_{r=a}+\frac{H}{\lambda}U(r,t)\bigg|_{r=a}=\frac{H}{\lambda}T_g(t) \tag{2}$$

where $T_g(t)$ is variable temperature of the hot gases which surround the sphere, H is the coefficient of the heat exchange (see Carslaw and Jaeger, 1959,Chapter I). Qualitative physical analysis shows that during the heating process the quantity $\lambda(\partial U/\partial r)_{r=a}$ must be positive, since the temperature on the surface of the sphere is greater in comparison with the temperature inside. Then must be $H[T_g(t)-U]_{r=a}>0$, which is very plausible, since the temperature of the gas is greater than the temperature of the sphere. The temperature of the atmospheric plasma can attain about 10^3 K. This process resembles quantitatively situation which occurs when a sphere is heated in the flame of a gas burner, or in combustion cell. The temperature on the surface of the sphere can reach for a short time the melting temperature, which is evident from the surface crust of meteorites dropped on the earth. This critical case of melting and reduction of the mass of the sphere will be not considered in our model. The solution of the partial differential equation (1) with zero initial condition and boundary condition (2) can be performed exactly by a standard method described e.g. in Carslaw and Jaeger (1959). So we present it in an abbreviated form. At first we introduce auxiliary radial function $V(r,t)$, which links to the temperature $U(r,t)$ by the formula:

$$U(r,t) = r^{-1}V(r,t). \tag{3}$$

Then equation (1) gives for $V(r,t)$:

$$\frac{\partial^2 V}{\partial r^2} = \frac{1}{\varkappa}\frac{\partial V}{\partial t}. \tag{4}$$

The boundary condition (2) is transformed into form:

$$a\left[\frac{\partial V}{\partial r}\right]_{r=a} + (aH\lambda^{-1} - 1)V(a,t) = a^2\lambda^{-1}HT_g(t). \tag{5}$$

Equation (4) we will solve by means of Laplace transform introduced by the integral formula:

$$\mathcal{L}\left\{V(r,t)\right\} = \int\limits_0^\infty V(r,t)e^{-pt}\,\mathrm{d}\,t = \overline{V}(r,p). \tag{6}$$

If the initial value of $V(r,t)$ (as well as initial temperature) is considered as zero, the solution of eq. (4) is:

$$\overline{V}(r,p) = \overline{A}\sinh(r\sqrt{p/\varkappa}), \tag{7}$$

where $\overline{A}$ must be determined from the Laplace transform of boundary condition (5):

$$a\left[\partial\overline{V}/\partial r\right]_{r=a} + (\lambda^{-1}Ha - 1)\overline{V}(a,p) = a^2\lambda^{-1}H\overline{T}_g(p), \tag{8}$$

and $\overline{T}_g(p)$ is Laplace transform of the function $T_g(t)$. Then we will obtain

$$\overline{A}(p) = a^2h\overline{T}_g(p)/\overline{G}(p), \tag{9}$$

where

$$\overline{G}(p) = a\sqrt{p/\varkappa}\cosh(a\sqrt{p/\varkappa} + (ha-1)\sinh(a\sqrt{p/\varkappa}). \tag{10}$$

The Laplace transform of temperature $\overline{U}(r,p) = r^{-1}\overline{V}(r,p)$ is:

$$\overline{U}(r,p) = r^{-1}a^2h\overline{T}_g(p)\sinh(r\sqrt{p/\varkappa})/\overline{G}(p). \tag{11}$$

Since the Laplace inversion of $\overline{T}_g(p)$ is considered as known $T_g(t)$ we have to determine the Laplace inversion of function $\sinh(r\sqrt{p/\varkappa})/\overline{G}(p)$. Analysis of this function in the complex plane p shows that this function is unique and has simple poles in roots of $\overline{G}(p)$ given by (10). These poles are discrete values:

$$p_n = -\xi_n^2\varkappa/a^2, \quad a\sqrt{p_n/\varkappa} = i\xi_n. \tag{12}$$

The p_n values can be obtained as roots of transcendent equation $\overline{G}(p) = 0$, which leads to transcendent equation in real variable ξ:

$$\xi \cos\xi + (ha - 1)\sin\xi = 0, \tag{13}$$

where $h = H\lambda^{-1}$. Using convolution theorem for Laplace transform we will obtain Laplace inversion of (11) in the form of convolution integral, similar to those which is given in the Chapter IX in Carslaw and Jaeger (1959):

$$U(r,t) = h\,a \int_0^t T_g(t-\tau) M(r,\tau)\,\mathrm{d}\,\tau. \tag{14}$$

Here the kernel function is in the form of infinite series:

$$M(r,\tau) = 2t_*^{-1} \sum_{n=1}^{\infty} e^{-\tau\xi_n^2/t_*} \frac{\xi_n^2 a r^{-1} \sin(r\xi_n/a)}{[\xi_n^2 + ha(ha-1)]\sin(\xi_n)}, \tag{15}$$

where $t_* = a^2/\varkappa$ is the characteristic time of the heat conduction, $ha = aH/\lambda$ is the factor of the heat transport from the surface of the sphere. We note that the kernel function $M(r,t)$ is Laplace inversion of the function $ar^{-1}\sinh(r\sqrt{p/\varkappa})/\overline{G}(p)$. The transcendent equation (13) has for $\xi > 0$ an infinite number of roots, which can be found numerically for various values of parameter $C = ha - 1$. First five root values of them can be found in the Table 2 of Appendix 4 in (Carslaw and Jaeger, 1959), but in our FORTRAN program we calculated these values till $n = 200$. Now let us put our attention to the temperature function $T_g(t)$. As physically plausible we suppose this function in the form:

$$T_g(t) = T_0 e^{-\alpha t} \times (\alpha t), \quad \alpha > 0, \quad t > 0. \tag{16}$$

It corresponds to gradual increase of temperature to the maximum $T_0\, e^{-1}$ at the time $t_0 = 1/\alpha$, then slowly decreased to zero, i.e. meteoroid is braked in more dense atmosphere. For this time excitation function we can easily obtain its Laplace transform

$$\overline{T}_g(p) = T_0\alpha \int_0^{\infty} t e^{-\alpha t} e^{-\beta t}\,\mathrm{d}\,t = \frac{T_0\alpha}{(p+\alpha)^2}. \tag{17}$$

The temperature function (16) can be introduced into convolution integral (14), but more suitable is calculate Laplace inversion of (11) using $\overline{T}(p)$ from (17). Then we must evaluate the Bromwich integral:

$$\frac{1}{2\pi\,\mathrm{i}} \int_{\sigma-\mathrm{i}\,\infty}^{\sigma+\mathrm{i}\,\infty} \frac{e^{pt}\alpha}{(\alpha+p)^2} \frac{\sinh(r\sqrt{p\varkappa})}{\overline{G}(p)}\,\mathrm{d}\,p = W(t), \quad \sigma = 0. \tag{18}$$

The meromorphic function which we have to integrate using residui theorem has second order pole at the point $p_\alpha = -\alpha$ and in the single roots $G(p)$ at $p_n = -\xi_n^2 \varkappa / a^2 = -\xi_n^2 / t^*$ given by (12)

$$W(t) = \operatorname{res}\left\{\frac{e^{pt}\alpha \sinh(r\sqrt{p/\varkappa})}{(\alpha+p)^2\overline{G}(p)}\right\}_{p=-\alpha} + \sum_{n=1}^{\infty} \operatorname{res}\left\{\frac{e^{pt}\alpha \sinh(r\sqrt{p/\varkappa})}{(\alpha+p)^2\overline{G}(p)}\right\}_{p=p_n}. \tag{19}$$

The residuum theory for the second order pole $p = -\alpha$ gives:

$$\begin{aligned}
\operatorname{res}\left\{\frac{e^{pt}\alpha \sinh(r\sqrt{p/\varkappa})}{(\alpha+p)^2\overline{G}(p)}\right\} &= \lim_{p\to-\alpha}\frac{\mathrm{d}}{\mathrm{d}\,p}\left\{\frac{e^{pt}\alpha \sinh(r\sqrt{p/\varkappa})}{(\alpha+p)^2\overline{G}(p)}(\alpha+p)^2\right\} = \\
= F_1(r,t) = \alpha\, t\, e^{-\alpha t}\,\frac{\sin(\frac{r}{a}\sqrt{\alpha t_*})}{B(a,\alpha t_*)} &- \frac{1}{2}e^{-\alpha t}\,\frac{(r/a)\sqrt{\alpha t_*}\cos(\frac{r}{a}\sqrt{\alpha t_*})}{B(a,\alpha t_*)} + \\
&+\frac{1}{2}e^{-\alpha t}\,\frac{\sin(\frac{r}{a}\sqrt{\alpha t_*})\left[ha\cos\sqrt{\alpha t_*} - \sqrt{\alpha t_*}\sin\sqrt{\alpha t_*}\,\right]\sqrt{\alpha t_*}}{[B(a,\alpha t_*]^2}
\end{aligned} \tag{20}$$

where $B(a,\alpha t_*) = \sqrt{\alpha t_*}\cos(\sqrt{\alpha t_*}) + (ha-a)\sin(\sqrt{\alpha t_*})$. The infinite number of single poles $p_n = -\xi_n^2/t_*$ give the second part of inversion (18):

$$\begin{aligned}
F_2(r,t) &= \sum_{n=1}^{\infty}\lim_{p\to p_n}\left\{\frac{\alpha\, e^{pt}\sinh(r\sqrt{p/\varkappa}}{(\alpha+p)^2\overline{G}\,\mathrm{d}(P)}\right\} = \\
&= \sum_{n=1}^{\infty}\frac{(\alpha t_*)e^{-\xi_n^2 t/t_*}\xi_n^2\sin(\xi_n r/a)}{\left[\alpha t_* - \xi_n^2\right]^2\left[\xi_n^2 + (ha-1)ha\right]\sin(\xi_n)}.
\end{aligned}$$

Then the final expression for the temperature inside of sphere is:

$$U(r,t) = T_0 ha\left\{(a/r)F_1(r,t) + (a/r)F_2(r,t)\right\}. \tag{21}$$

This expression is bounded for all values $r \in \langle 0, a\rangle$. The advantage of this formula lies in more rapid convergence of infinite series (20) in comparison with (15). Moreover, this hold true for the calculation of temperature gradient inside of sphere. For calculation of $\partial U(r,t)/\partial r$ we need three r-derivatives:

$$\begin{aligned}
\frac{\partial}{\partial r}\left\{\left(\frac{a}{r}\right)\sin\left(\frac{r}{a}\sqrt{\alpha t_*}\right)\right\} &= -\frac{a}{r^2}\sin\left(\frac{r}{a}\sqrt{\alpha t_*}\right) + \frac{\sqrt{\alpha t_*}}{r}\cos\left(\frac{r}{a}\sqrt{\alpha t_*}\right) \\
\frac{\partial}{\partial r}\left\{\cos\left(\frac{r}{a}\sqrt{\alpha t_*}\right)\right\} &= -\frac{\sqrt{\alpha t_*}}{a}\sin\left(\frac{r}{a}\sqrt{\alpha t_*}\right) \\
\frac{\partial}{\partial r}\left\{\left(\frac{a}{r}\right)\sin\left(\xi_n\frac{r}{a}\right)\right\} &= -\frac{a}{r^2}\sin\left(\xi_n\frac{r}{a}\right) + \frac{\xi_n}{r}\cos\left(\xi_n\frac{r}{a}\right).
\end{aligned}$$

All these expressions have zero limit for $r \to 0$. Careful analysis shows that the boundary condition (2) for $r = a$ is satisfied. Using these formulae we

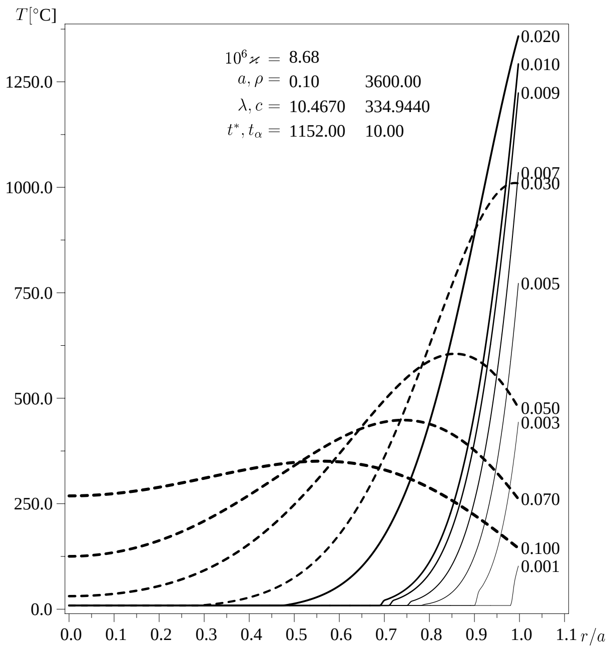

Figure 5. Radial distribution of the temperature inside the sphere for various times. The numeration of curves denotes $(t/t^* = t\varkappa/a^2)$.

performed numerical calculations of $U(r,t)$ and $\partial U(r,t)/\partial r$ for various values of t/t_*. In Figs.5-7 we present numerical results for the sphere of radius $a = 0.1$ m. The thermal parameters, the heat induction λ, the density ρ, the specific heat of material c, the thermal diffusivity ($\varkappa = \lambda/(\rho.c)$) were chosen close to the parameters ultrabasic rocks, i.e. as follows: $\lambda = 10.467\,\mathrm{Js^{-1}m^{-1}K^{-1}}$, $\rho = 3600\,\mathrm{kg\,m^{-3}}$, $c = 334.944\,\mathrm{J\,kg^{-1}K^{-1}}$ which gives $t_* = a^2/\varkappa = 1152\,\mathrm{s}$.

Full curves in Fig.5 show the radial dependence of the temperature for the heating times $t \sim 2t_0$. The temperature curves after the time $2t_0$ are depicted by broken lines. From Fig.5 it is clear that there exists some time interval in which the sphere in almost half of its radius was heated to the temperatures above or close to the Curie temperatures 500–600°C. When the surface heating was stopped these temperatures progressed in attenuated form into the central region of the sphere. Here we can see that the thermal regime of the sphere is controlled by two characteristic time constants $t_* = a^2/\varkappa$ – characteristic time of the heat propagation in the sphere and by $t_\alpha = 1/\alpha$, where α is the exponential factor of the surface gas temperature (16).

In Fig.6 we present temperature gradient curves ($\partial U/\partial r$) in °C/mm pertinent to the temperature curves depicted in Fig.5. For better clarity of results we present in Fig.7 the time courses of temperature of surrounding hot gas

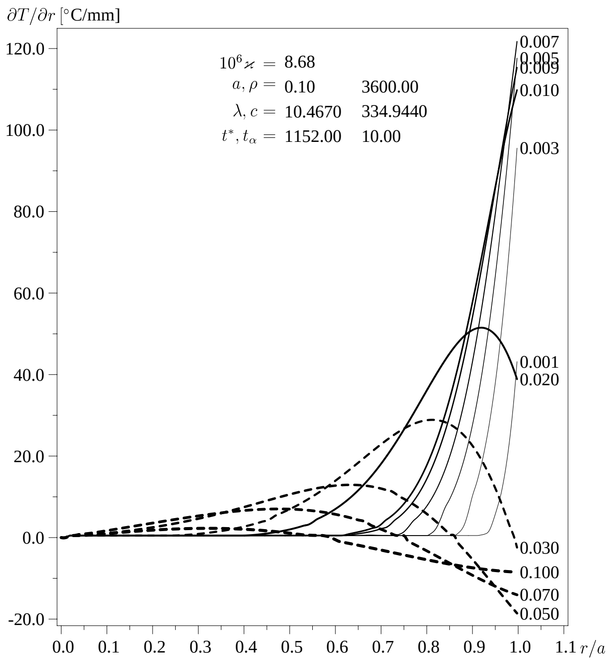

Figure 6. Radial distribution of the temperature gradient inside the sphere for various times. The numeration of curves denotes ($t/t^* = t\varkappa/a^2$).

$T_g(t)$ as well as for the surface of the sphere and for the level 1 cm below the surface ($r/a = 0.9$). For the level $r/a = 0.9$ we present the time course of temperature gradient also. We can see that the calculated gradients can attain values till 130°C/mm, but it concerns the stage when the surface temperature is above 1000°C, which means melting and ablation of rock material there. In depths which correspond to 10 mm below the surface ($r/a \doteq 0.9$) the gradient values attain 40–60°C/mm, which is well compared with experimental data (∼ 50°C/mm) determined for the Kirine meteorite by Melcher (1979).

4. Discussion

The main carrier of RM of H3-5 Fermo chondrite breccia, as inferred from Curie temperature measurements and the results of the thermal demagnetization of samples is probably the taenite (γ phase). The kamacite (α phase) is also present in Fermo, but is not able to acquire and carry the TRM, because there is actual a transformation from α phase to γ phase at high temperatures (700 to about 600°C; Orlický et al., 2000). This transformation is linked probably with a distortion of the elementary lattice of the α phase during this process

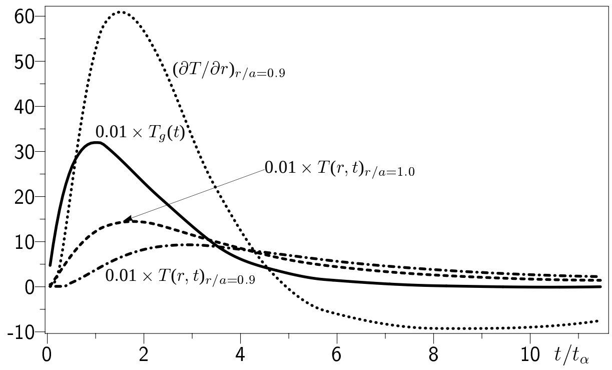

Figure 7. Time evolution of the temperature (multiplied by factor 0.01) of the hot gas $T_g(t)$ – full line, surface temperature of the sphere $T(r,t)$ for $r = a$ – dashed line, temperature at radius $r = 0.9 \times a$ – dash dotted line. The dotted line is time course of the temperature gradient (in °C/mm) at radius $r = 0.9 \times a$.

(Vonsovskij, 1971). The individual samples differ slightly in magnetic susceptibility (κ). While there is approximately equal contribution of both taenite and kamacite to the κ of the meteorite at laboratory temperature, the taenite is only one remanent magnetization bearing NiFe alloy in the meteorite . Maybe there is a higher content of the taenite within the samples with higher intensities of NRM, except of more distinctly confined NiFe grains within the groundmass, compared with samples hawing lower intensities of NRM.

These inhomogeneties in contents of the taenite and kamacite are probably linked with the stadium of forming the chondrite breccia within extraterrestrial conditions. The Thellier method was effective only in the interval of 450–550°C. While the thermal demagnetization of NRM of samples does follow quite well in the applied interval from 25–550°C, an acquisition of PTRM in a laboratory field has not obeyed the Thellier's rule in the interval of 25 to cca 350–400°C. Different values of the coefficient k ($k_1 = 1.97$ and $k_2 = 1.17$ for the sample 1 and 2, respectively) were derived using the Thellier method. There maybe an alteration of the troilite to magnetite due to heating of the sample on air over 400°C. We assume that except of the taenite, which is the dominant carrier of RM, a presence of the secondary magnetite contributes and distorts TRM or PTRM of the Fermo meteorite. The paleointensity for Fermo was found to be about F = 0.0752 mT. A comparison of data from the previous work (Orlický et al., 2000) results in an idea that NRM of Fermo was induced in a magnetic field of the paleointensity near F = 0.0467 mT, what is of course less of 0.0285 mT than F = 0.0752 mT derived by other way.

A mathematical model for penetration of temperature inside a spherical meteoroid heated from its surface (neglecting the ablation process) has been derived on the basis of solution of the heat conduction equation in the spherical co-ordinate system. Qualitative analysis shows that during the heating process the quantity of the heat exchange must be positive, since the temperature on the surface of the sphere is greater than the temperature inside of the sperical body. The temperature of the atmospheric plasma can attain about 10^3 K. The temperature on the surface of a meteoroid can reach the melting temperature of the FeNi alloys and some matrix of the meteoroid.

A melting and reduction of the mass of the meteoroid have not been considered in our model. The presented mathematical model has shown that there exists some time interval in which the sphere in almost of half of its radius was heated to the temperatures above or close to the Curie temperature of taenite (500–600°), however, due to real reduction and mass loss of the meteorite during its flight through the atmosphere, the total process is substantially accelerated. This means that when the meteoroid becomes so hot (500–600°C) any kind of eventual extraterrestrial magnetizations have not been able survived. They completely disappear. New RM probably of the thermoremanent (TRM) origin was induced by the geomagnetic field after fall of meteorite on the earth surface.

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