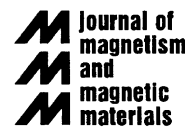




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Comparative magnetic measurements on social insects

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Abstract

Biogenic magnetite has been detected in several species of social insects and may well form the basis of a magnetic sensory system in these animals, although other physiological functions are possible, too. We report here on hysteresis measurements on honeybees (*Apis mellifera*) and the termite *Neocapritermes opacus*. The ratio of saturation remanence to saturation magnetization, J_{rs}/J_s , was determined as 0.11 (0.15) in bees (termite), the coercive force H_c as 90 (50 Oe). The magnetic remanence is generally low (of the order of 10^{-6} emu per individual). The values obtained are similar to the ones reported previously on a migratory ant species, which suggests that biomineralization of magnetic material in social insects may underlie a generic process.

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Social insects have been reported to be influenced by magnetic fields [1] and to be capable of using the geomagnetic field for orientation, foraging, migration, etc [2]. The mechanisms underlying magnetic-field reception and transduction into physiologically exploitable signals, however, remain elusive. To test if ferromagnetic material may in principle be involved in magneto-reception, magnetic measurements have been performed on several species of insect to detect, localize, and characterize magnetic material [3–8]. *Apis mellifera* honeybees were the first social insects in which magnetic remanence was detected [3,4]. Recently, magnetic

material has been characterized in a Meliponinae bee, *Schwarziana quadripunctata* [9], as well as in different species of ant [7,8,10,11] and termite [5,6,12]. As pointed out in the recent literature, the interpretation of magnetic measurements on insects is far from straightforward because magnetic material is detected in highly variable volume concentrations, reflecting differences in insect age, size, diet, function in the colony, etc. as well as seasonal and local effects. This variability is particularly pronounced in *Neocapritermes opacus* termites, which live in subterranean nests and forage for dry powdered wood inside fallen trunks [13]. With such a diet, a relatively strong magnetic signal from ingested particles can obscure a potential magnetic signal from intrinsically synthesized (biomineralized) material. We here report on magnetic measurements on *N. opacus* under cellulose diet

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(filter paper) and honey bees (*A. mellifera*) and compare our results with those obtained on social insects that have not been subject to a special diet.

Naturally dead honeybees *A. mellifera* were collected on the ground beneath the entrance to the hive at São Paulo University. Bees were extensively washed with 80% (v/v) ethanol solution to remove particles in the fur. To prevent deterioration of their tissue, the honeybees were dried for 10 h at 35 °C and for 21 h at 39 °C. The dried samples were kept in a desiccator until used. *N. opacus* workers were collected in the forest at Santa Genebra Reserve, Campinas, Brazil. To eliminate ingested material in their guts, some of the collected termites were fed with cellulose until they died after 1 day and after 5 days, respectively; the corresponding samples are referred to as *N1* and *N5* (see in Table 1). The termite sample with no cellulose diet applied is named *N0*. The dead termites were kept in cacodylate buffer (0.1 M, pH 7.4) and dried just before measurement. All the magnetic measurements were conducted with a Quantum Design MPMS SQUID magnetometer. Room temperature hysteresis loops were obtained with the magnetic field applied perpendicular to the long body axis of the insect samples. The measurements on bees were performed in the parallel orientation, yielding less noisy magnetization curves than in the perpendicular orientation. The linear contribution in the high-field range was subtracted from all hysteresis loops. Fig. 1 shows the slope-corrected hysteresis loops. The corresponding values of magnetic susceptibility are given in Table 1.

While honeybee and the termite sample *N5* show diamagnetic behaviour at high fields, as previously reported for a migratory ant [6], the samples *N1* and *N0* are paramagnetic. The paramagnetic contribution in *N1* is reduced compared to *N0* and has disappeared altogether in *N5*, which gives a first hint that the cellulose diet was efficient at clearing the digestive tract of the termites from ingested particles. Similarly, the saturation magnetization J_s decreased by two orders of magnitude from *N0* to *N1* and *N5*. When normalized the curves *N1* and *N5*, coincide well within the experimental errors, as shown in the low-field region curve (Fig. 2). Although a progressive reduction in J_s was expected

with longer application of the special diet, J_s of *N1* is slightly higher than J_s of *N5*. The number of samples is still too small to allow for statistically significant conclusions and further systematic research is necessary to determine magnetic properties as a function of individual insect characteristics such as age, size, function in the colony, etc. On the other hand, it is possible that the special diet induces physiological adaptation mechanisms in the insects.

Apart from reducing J_s , the cellulose treatment removes hard magnetic material as indicated by the drop in coercive field H_c from values about 110 Oe to values between 48 and 60 Oe (Table 1, Fig. 2). Consistent with the decrease in H_c , the ratio J_{rs}/J_s is reduced, too, albeit by a lesser degree. The hysteresis loop on *N0* is wasp-waisted, which confirms the presence of at least two magnetic components with different coercive force [6]. Compared to the cleaned termite samples, the honeybee sample has larger H_c and J_s but similar values of J_{rs}/J_s .

It is interesting to compare the above results with the ones published on other species of social insect. The species investigated most thoroughly is the migratory

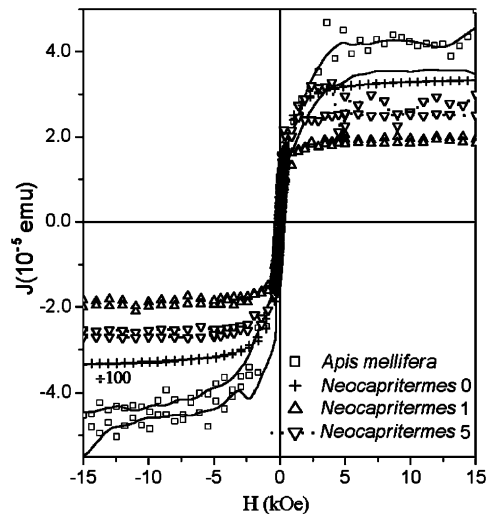


Fig. 1. Room-temperature hysteresis loops.

Table 1

Magnetic hysteresis parameters of social insects, measured at room temperature (293–310 K)

Sample	H_c (Oe)	J_s (10^{-5} emu)	J_{rs} (10^{-5} emu)	J_r/J_s	χ (10^{-10} emu/Oe)
<i>Neocapritermes opacus</i> , <i>N0</i> [6]	107–115	330–340	600–680	0.18–0.21	250
<i>Neocapritermes opacus</i> , <i>N1</i>	48–55	1.8–2.0	2.7–2.9	0.13–0.16	4.1
<i>Neocapritermes opacus</i> , <i>N5</i>	50–60	2.5–2.9	3.9–4.8	0.13–0.19	–6.7
<i>Apis mellifera</i> (parallel orientation)	83–103	3.5–4.3	4.1–5.1	0.09–0.14	–2.85
<i>Pachycondyla</i> [6]	53–65	1.3–1.7	1.5–2.5	0.09–0.19	–9.2

With exception of *A. mellifera*, all samples were oriented with that their long body axis perpendicular to the magnetic field.

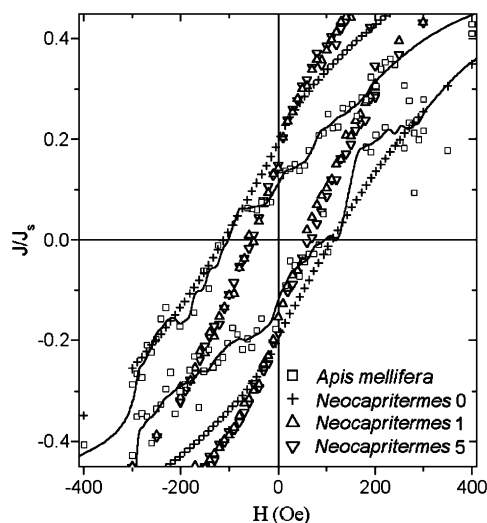


Fig. 2. Low-field region of hysteresis curves.

ant *Pachycondyla marginata*, which feeds exclusively on *N. opacus*. *P. marginata* has magnetic properties similar to its prey after cellulose diet (Table 1). The presence of superparamagnetic (SP) particles in the abdomen of *P. marginata* has been inferred from electron paramagnetic resonance measurements, which yielded an average magnetic grain size of 13 nm and larger, elongate particles or aggregates of three particles [11]. Using transmission electron microscopy (TEM), the average particle dimensions of magnetite crystals extracted from *P. marginata* samples collected at the same nest was determined as 39 nm in length and 27 nm in width [7]. The most likely reason for the discrepancy in grain size is that the magnetic extraction procedure is less effective for SP particles than for stable single-domain particles. Likewise, the magnetically determined volume may differ from the one measured under the TEM. Recent hysteresis measurements yielding wasp-waisted hysteresis loops confirmed the presence of a mixed magnetic system in *P. marginata* [8].

Magnetite particles extracted from the Australian termite *Nasutitermes* and *Amitermes* had a narrow distribution of grain size around 10 nm [5]. Interestingly, *Amitermes* were able to carry a magnetic remanence after exposure to strong magnetic fields, which does not appear to be in agreement with SP particles. The magnetic remanence curves measured on *Amitermes* pointed to magnetic interactions between the particles, due probably to clustering of grains, which would raise the average magnetic grain size of the SP particles above the SP-SD threshold size.

A comparison of the magnetic parameters of *A. mellifera* bee with those of other social insects listed in the table is not straightforward because acceptable magnetization curves on *A. mellifera* were only obtained

on individuals oriented parallel to the applied magnetic field and the magnetic properties of social insects have shown to be anisotropic [3,6]. Therefore, it is not clear if the magnetic material in *A. mellifera* generally is magnetically harder ($H_c = 93$ Oe) than that in the migratory ant *P. marginata* ($H_c = 59$ Oe), or if it is similar magnetic material arranged in a different manner or orientation with respect to the applied field direction.

Overall, the results (Table 1) point to similar type and concentrations of magnetic material in the different species of social insect studied. Whilst magnetic measurements cannot be employed to unambiguously identify the nature and function of magnetic material in the tissue, they are very useful for preliminary screening and quantifying. We will further our magnetic measurements with TEM and magnetic force microscopy (MFM) investigations to identify the nature of the magnetic material, the arrangement of particles in the tissue, and connection in the nervous system. This way, we should be able to clarify whether or not the magnetic material may form the basis of magnetic-field reception in social insects, or whether it has a different physiological function unknown thus far, be it in gravity receptors or in iron metabolism.

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References

- [1] R. Wiltschko, W. Wiltschko, *Magnetic Orientation in Animals*, Springer, Berlin, 1995.
- [2] M. Vacha, *Biologia Bratislava* 52 (1997) 629.
- [3] J.L. Gould, J.L. Kirschvink, K.S. Deffeyes, *Science* 201 (1978) 1026.
- [4] J.L. Kirschvink, J.L. Gould, *Biosystems* 13 (1981) 181.
- [5] B.A. Maher, *Proc. R. Soc. London, Ser. B* 265 (1998) 733.
- [6] D.M.S. Esquivel, E. Wajnberg, G.R. Cernicchiaro, O.C. Alves, *J. Magn. Magn. Mater.* 278 (2004) 117.
- [7] D. Acosta-Avalos, E. Wajnberg, P.S. Oliveira, I. Leal, M. Farina, D.M.S. Esquivel, *J. Exp. Biol.* 202 (1999) 2687.
- [8] E. Wajnberg, G. Cernicchiaro, D.M.S. Esquivel, *BioMetals* 17 (2004) 467.
- [9] M. Lucano, E. Wajnberg, D.M.S. Esquivel *Proceedings of Ninth Joint MMM/Intermag Conference, 2004*, p. 464.
- [10] D.M.S. Esquivel, D. Acosta-Avalos, L.J. El-Jaick, A.D.M. Cunha, M.G. Palheiros, E. Wajnberg, M.P. Linhares, *Naturwissenschaften* 86 (1999) 30.
- [11] E. Wajnberg, D. Acosta-Avalos, L.J. El-Jaick, L. Abrãdo, J.L.A. Coelho, A.F. Bakuzis, P.C. Morais, D.M.S. Esquivel, *Biophys. J.* 78 (2000) 1018.
- [12] O.C. Alves, E. Wajnberg, J.F. de Oliveira, D.M.S. Esquivel, *J. Magn. Res.* 168 (2004) 246.
- [13] R.L. Araujo, 12, in: K. Krishna, F.M. Weesner (Eds.), *Biology of Termites*, vol. 2, Academic Press, New York, 1969 (Chapter 12).