Modeling the Electric and Dielectric Behaviors of the Gebel Kamil Iron Meteorite

Bassem S. Nabawy ^{1,2}

Received 1 August 2021; accepted 20 December 2021
Published online: 28 January 2022

The Gebel Kamil iron meteorite is a famous big meteorite, and it is considered among the rare well-preserved iron meteorites. In this study, its electric and dielectric properties, namely electric conductivity (σ), dielectric constant (ϵ'), and dielectric loss (ϵ''), were measured using alternating current at a wide range of frequencies (50 Hz–11.0 MHz). This electrical characterization process was performed to get a diagnostic electric behavior of the electric and dielectric parameters as a function of the applied frequency (f). It is revealed that, by increasing f , the σ increased, while the dielectric properties decreased systematically through three stages of frequency. The well-known octahedral structure of iron meteorites was imaged using scanning electron microscopy (SEM) with support by energy-dispersive X-ray analysis (EDAX) to analyze the chemical composition of the meteorite specimen. The EDAX indicated that the Gebel Kamil meteorite is a Ni–Fe alloy with no impurities (Ni = 20.4–22.3%, Fe = 77.7–79.6%). This chemical composition and the electric and dielectric behaviors of the studied Ni-rich Gebel Kamil meteorite specimen can be recorded as diagnostic features and properties of this Fe–Ni meteorite.

KEY WORDS: Gebel Kamil meteorite, Fe–Ni meteorite, Electric conductivity, Dielectric constant, SEM.

INTRODUCTION

Recently, the nondestructive physical properties, including density and porosity, of more than 1100 meteorite samples were reported in the literature by many authors (e.g., Kukkonen & Pesonen, 1983; Britt et al., 2002; Britt & Consolmagno, 2003; Consolmagno et al., 2006, 2008a, 2008b, 2008c; Kohout et al., 2008; Macke, 2010; Macke et al., 2010a, 2010b, 2011a, 2011b, 2016; Flynn et al., 2018; Ostrowski & Bryson, 2019). According to Macke (2010), the high-density Fe metal-rich H chondrites are susceptible to weathering and alteration pro-

ducing low-density Fe oxide (3.45–4.40 g/cm³, Macke et al., 2010b).

Besides, a few articles have been published on the physical properties of enstatite chondrites, a rare form of meteorites, which are characterized partly by an abundance of FeO-free enstatite, as a member of the pyroxene–silicate mineral series, and its intermediate composition ((Mg,Fe)SiO) (Macke et al., 2010b). These properties include only porosity, density, and magnetic susceptibility. The density of enstatite chondrites is relatively high, ranging from 3.17 to 4.46 g/cm³, with majority falling between 3.5 and 3.8 g/cm³ (Bland et al., 1998; Consolmagno et al., 1999; Macke et al., 2010b). However, the grain density of iron meteorites (7.44–7.91 g/cm³; Nabawy & Rochette, 2016) is much higher than that of chondrites and, in turn, their physical properties (e.g., electric properties) are

¹Department of Geophysical Sciences, National Research Centre, 33 ElBohouth street, P.O. 12311 Dokki, Cairo, Egypt.

²To whom correspondence should be addressed; e-mail: bsnabawy@yahoo.co.uk

much different from those of enstatite chondrites. This differentiation is due to the low Fe and Ni content in chondrites and their intermediate composition ((Mg,Fe)SiO) (Piqué & Trigo-Rodríguez, 2004).

Iron meteorites are shiny, rustless, and dense and contain some Ni content. The Ni content varies primarily between 4 and 28% by weight but may reach up to 60% by weight (Goldstein et al., 2009; Scott, 2013; Nabawy & Rochette, 2016; Fry et al., 2018). The shiny appearance and octahedral structures are among the most diagnostic features of most Fe–Ni meteorites. These octahedral structures are due to exsolution of the kamacite lamellae within taenite crystals (D’Orazio et al., 2011; Scott, 2013; Fry et al., 2018). Iron meteorites carry a lot of information about their different celestial precursors and history (Bland et al., 2002; Verma & Tripathi, 2004), but despite this important information only few density and porosity measurements have been published in the literature (Fry, 2013; Fry et al., 2018). Besides, the literature is rarely devoted to electric properties of iron meteorites as a function of variable frequencies of alternating current (AC) in what is called electric prints (Nabawy & Rochette, 2016; Ostrowski & Bryson, 2019). This electric behavior is thought to be diagnostic for the different iron meteorites based on their variable Ni content, internal structure, temperature, and the applied AC frequency. Therefore, the dielectric constant (ϵ') and electrical resistivity measured at variable frequencies can be used to characterize iron meteorites. This electric technique is fast enough to be used to quantify the Ni content of iron meteorites based on their electric properties (Nabawy & Rochette, 2016). The scarcity of this type of measurement is attributed mostly to the fact that meteorite samples should be cut into standard geometric shapes, which is considered among the main drawbacks of this type of measurements (Tehro et al., 1993; Nabawy & Rochette, 2016; Fry et al., 2018).

The Gebel Kamil meteorite that was discovered near Gebel El-Oweinat in the southwest of the Western Desert of Egypt is considered one of the most common iron meteorites in Egypt. It has been discovered and studied by Folco et al., (2010, 2011). Its petrography, mineralogy, and geochemical analyses were studied in detail by D’Orazio et al. (2011). It is reported that thousands of meteorite specimens were collected from the meteorite crater and from its surrounding areas up to 1.6 km of the crater in SW Egypt, where a total mass of 1700 kg, of dif-

ferent size specimens, was collected by Folco et al., (2010, 2011). Its crater is located in a rocky and sandy land at East El-Oweinat area in SW Egypt (22°01'06" N, 26°05'15" E) at about 600 m above the sea level.

D’Orazio et al. (2011) mentioned that the Gebel Kamil meteorite is a Ni-rich (~ 20 wt% Ni) ataxite with high Ga and Ge content and a very fine-grained duplex plessite metal matrix. Due to the scarcity of electric studies on meteorites and due to the good preservation and importance of the Fe–Ni Gebel Kamil meteorite, the present paper aimed to study its electric properties (electric conductivity and dielectric properties) as a function of the applied frequency (f). It is considered an extension of the study by Nabawy and Rochette (2016) on the electric behavior of the Mundrabilla and Gibeon iron meteorites, but on a much wider electric frequency range (50 Hz–11.0 MHz) than that applied before (50 Hz–100 kHz).

METHODOLOGY

To reveal the internal microstructure of the studied Gebel Kamil meteorite, a small piece of the meteorite was etched chemically using a prepared etching solution of 1% HF + 1% HNO₃ for only one second. It was then dehydrated and coated with gold and studied using SEM (scanning electron microscopy) of Model Quanta 250 EG in the Central Labs of the National Research Centre of Egypt. The SEM is operated in the acceleration voltage range of 1–30 kV and equipped with a field emission gun, a secondary electron detector with resolution up to 2.0 nm, an electron backscattering pattern detector (EBSP), and EDAX (energy-dispersive X-ray spectrometer) to reveal the elemental chemical composition of the studied meteorite with atomic numbers down to carbon atom.

For studying the electric properties and revealing the electric behavior as a function of the applied AC frequency, a meteorite piece was prepared as a slab of two parallel polished and smoothed surfaces of thickness 4.55 mm. The prepared sample was then cleaned and dried at 60 °C for 48 h. The meteorite sample was then introduced into a ceramic holder of two non-polarizing electrodes of resistivity less than 0.5 Ω , and the capacitance effect (C_p), electric loss tangent (D), and the electric resistivity (R_p) were measured in a parallel arrangement at room temperature, using a digital

computerized LCR HiTESTER impedance analyzer (GmbH & Co. KG, high-resolution alpha analyzer) of measuring range 0.01 Hz–20 MHz in the Department of Geophysical Sciences, the National Research Centre of Egypt. Measurements were conducted at 250 selected frequencies in the range of 50 Hz–11.0 MHz. Measurements were repeated six times, and the average was then taken in high accuracy. A silver paste was applied to fill the air gaps, if found, between the sample surface and the electrode. The electric conductivity (σ), ε' , and dielectric loss (ε'') of the meteorite were then estimated, respectively, as

$$\sigma = \frac{L}{AxR_p} \quad (1)$$

$$\varepsilon' = \frac{C_p x L}{Ax\varepsilon_o} \quad (2)$$

$$\varepsilon'' = \varepsilon' x D \quad (3)$$

where R_p is the parallel electric resistance, A is the surface area of measuring electrode (diameter = 23 mm), L is the sample thickness (4.55 mm), C_p is the parallel electric capacitance, ε_o is the dielectric constant of air (8.85×10^{-12} F/m), and D is the measured electric loss tangent ($\tan \delta$).

RESULTS

SEM and EDAX

The mineral and chemical compositions and the solid microstructure of a given dry meteorite sample contribute primarily to its electric and dielectric properties. Thus, the electric and dielectric properties of the Gebel Kamil meteorite are mostly attributed to its conductive components (Nabawy & Rochette, 2016).

To check the chemical composition and solid fabric/microstructure of the present sample, it was investigated and analyzed by SEM to image its microstructure and by EDAX to determine its main constituents. The SEM at 2000 $\times$ and scale 25 μ m revealed that the Gebel Kamil meteorite is dominated by octahedral structure (Fig. 1). This structure is well known for iron meteorites as described by many authors (Farrington, 1901; Goldstein, 1965; Norton, 1998, 2008; Goldstein et al., 2009; Fry, 2013; Nabawy & Rochette, 2016; Fry et al., 2018). This

microstructure is attributed to the presence of two Fe–Ni phases, and to kamacite and taenite, which were separated from each other during the cooling process. Kamacite has a lower percentage of Ni compared to taenite. The latter solidifies at relatively high temperatures, while the former, in viscous nature till crystallization, at lower temperatures. The wider bands are primarily composed of kamacite and are easily dissolved on etching by acid mixture, revealing the diagnostic octahedral structure. Although this octahedral structure may be absent in many Fe–Ni meteorites, it is a diagnostic structure for many famous Fe–Ni meteorites.

The EDAX measurement at two spots indicated that the Ni content of the Gebel Kamil meteorite is relatively high (20.4–22.3%), while Fe is a complementary element in the studied fresh sample, with the highest peak and no additional impurities (Fig. 1) (Note: additional impurities may be noticed in other samples). The estimated Ni content, which corresponds to that already published by D'Orazio et al. (2011), was ~ 20 wt% Ni.

Electric Properties

The measured electric and dielectric values are shown in Table 1. The ε' , ε'' , and σ of the Gebel Kamil meteorite were plotted as a function of frequency in the range 50 Hz–11.0 MHz (Figs. 2, 3 and 4). The electric behavior of the studied meteorite can be subdivided into three stages: (1) Stage I is represented by a steady slope with slight change in values; (2) stage II is a transitional stage between stage I and stage III; and (3) stage III is represented by a steep slope with abrupt change in values. Because the σ increased with increasing f (Fig. 2), whereas the dielectric parameters decreased with increasing f , the behavior is inverse for both ε' and ε'' (Figs. 3, 4).

The transitional stages of ε' and ε'' have the same frequency limits (1.0–3.0 MHz, Figs. 3, 4) but are different for σ (8.0–10.5 MHz) (Fig. 2). A binomial inverse quadratic relationship was established for both dielectric parameters against frequency, while a trinomial proportional relationship was established for the conductivity–frequency relationship. It seems that the obtained electric behavior and the mathematical models of the σ – f relationship were more complex than the behavior and models of ε' – f and ε'' – f relationships.

Table 1. Electric properties of Gebel Kamil iron meteorite including electric conductivity (σ), dielectric constant (ϵ'), and dielectric loss (ϵ'') at different frequencies

	50 Hz	1.0 Hz	2.0 MHz	3.0 MHz	4.0 MHz	5.0 MHz	6.0 MHz	7.0 MHz	8.0 MHz	9.0 MHz	10 MHz	10.5 MHz	11 MHz
σ	0.010	0.012	0.015	0.017	0.033	0.034	0.035	0.051	0.065	0.244	0.364	0.626	1.237
ϵ'	1.194	0.325	0.184	0.114	0.079	0.059	0.045	0.036	0.029	0.024	0.020	0.017	0.013
ϵ''	1.874	0.105	0.048	0.019	0.011	0.08	0.005	0.004	0.003	0.002	0.002	0.002	0.001

Values of ϵ' and ϵ'' are $\times 10^{-6}$, and the unit of σ is S/cm

Figure 2. Electric conductivity (σ) of the Gebel Kamil meteorite versus the applied frequency.

DISCUSSION

Weathering and Chemical Composition

Although the Fe metal and its sulfide are sensitive to terrestrial chemical weathering and transformation to less shiny rusting materials, the present Gebel Kamil meteorite sample is considered among the rare Fe–Ni meteorite samples that succeeded to retain its original composition with no significant weathering by oxidation and cracking. The hand specimen was in a well-preserved non-weathered and fresh state with only a thin film of rust on its surface. This nature was indicated by its shiny brightness and pure Fe–Ni content in the prepared sample (Fig. 1). The SEM and EDAX data supported the fresh nature of the studied sample with 100% Fe–Ni content, which is responsible for forming the octahedral microstructure (20.4–22.3% Ni content, Fig. 1), and indicated the absence of Fe oxides or other terrestrial materials (i.e., ruling out any effective terrestrial weathering processes). This

fresh chemical composition has a relatively high Ni content like that published by Nabawy and Rochette (2016) for the Mundrabilla meteorite (31% Ni) and the Fe–Ni alloy (30% Ni) that was prepared by them for studying its electric resistivity. This well-preserved nature is attributed to its ineffective weathering history including the accumulation environment and fast burial (Bischoff & Geiger, 1995; Stelzner et al., 1999; Welten, 1999; Nabawy & Rochette, 2016).

However, it is worth mentioning that D’Orazio et al. (2011) mentioned that all the specimens of the Gebel Kamil meteorite they collected were in a partially oxidized state and that its pitted surface was due to wind erosion action and terrestrial weathering. They added that the overall freshness of the Gebel Kamil meteorite specimens, their scattering with no noticeable accumulations in the field, and the original status of the ejecta blanket and rays indicate the instant burial of the meteorite (Folco et al., 2010, 2011; D’Orazio et al., 2011).

Figure 3. Dielectric constant (ϵ') of the Gebel Kamil meteorite versus the applied frequency.

Electric and Dielectric Behavior of the Studied Meteorite

The free conductive electrons in solid materials carry an active energy charge that enforces them to move through the material by applying an outer source of current. This charged energy is a function of f ; it increases with increasing f (Nabawy & Rochette, 2016). Nabawy and Rochette (2016; Khater et al., 2019, 2020) studied the electric resistivity of some meteorites and prepared Fe–Ni alloys and assigned two main stages: pre-saturation low-frequency stage (mostly less than 1.0 kHz) and saturation high-frequency stage (higher than 1.0 kHz). They added that the electric behavior of the solid material is a diagnostic behavior related primarily to its chemical and internal structure. In the next sections, the behaviors of σ , ϵ' , and ϵ'' are discussed and presented as a function of f in a wide range of frequencies (50 Hz–11.0 MHz).

Electric Conductivity (σ)

Similar to study by Nabawy and Rochette (2016) of a Mundrabilla meteorite (31% Ni) and a Fe–Ni alloy (30% Ni) at 50–100 kHz, the electric behavior of the present sample was divided into three stages: (1) steady stage I (up to 8.0 MHz); (2) transitional stage (8.0–10.5 MHz); and (3) steep stage III (more than 10.5 MHz) with an abrupt increase in σ values (Fig. 2).

In general, the relatively high σ of the studied Gebel Kamil meteorites (varying from 0.01 to 1.237 S/cm (at 50 Hz and 11.0 MHz, respectively)) is related to its high metal content, which is rich with free electrons, and its sensitivity to increasing f . The high electronic activity of iron meteorites supports the simplicity of their electric behaviors with no thresholds or complex behavior with many peaks on the σ – f plot. However, some peaks are noticed in the transitional stage at 8.0–10.5 MHz (Fig. 2). These peaks may be explained by the Maxwell–Wagner polarization mechanism, where a separation of charged ions occurs, i.e., ions become freer to rotate with increasing f causing more contribution to σ .

Figure 4. Dielectric loss (ϵ'') of the Gebel Kamil meteorite versus the applied frequency.

(Kremer and Schonhals, 2003; Nabawy, 2018; Khater et al., 2019).

The increase in σ at relatively low frequencies in the steady stage I was estimated to be six times higher than the initial one (from 0.010 to 0.065 S/cm, Table 1), while it increased by about 10 times more in the transitional stage II (from 0.065 to 0.626 S/cm). This abrupt increase in σ at 8 MHz and higher may be attributed to increasing f and shifting of the sample behavior from the electronic and ionic polarization stages to the dipolar stages with much higher electronic activity.

Mathematical modeling of the σ of the Gebel Kamil meteorite as a function of f at the three mentioned stages is a valuable output of the present study, which enables estimation of σ as a function of f (Fig. 2). The constant values and complexity of these obtained mathematical models increased at higher frequencies due to increasing activity of free-charged electrons. However, this set of mathematical models is characterized by high reliability (i.e., $R^2 \geq 0.929$, Fig. 2) and a much wider frequency range (up to 11.0 MHz) than that applied by Nabawy and Rochette (2016) (up to 100 kHz).

Dielectric Constant (ϵ')

The Fe-rich Gebel Kamil sample was expected to have a relatively high ϵ' in comparison with the other solid materials. This is attributed to its relatively high charged free electrons. A slight decrease in the measured ϵ' was noticed with increasing f (cf. Khater et al., 2019, 2020). In contrast, the decrease in measured ϵ' of the Gebel Kamil meteorite was much steeper (from 1.19 at 50 Hz to 0.013 at 11.0 MHz) compared to that of many other porous materials. This can be attributed to the richness of this iron meteorite in free movable charges that move faster and faster on increasing f . The abrupt decrease in ϵ' at the low frequencies of the steep stage I (50 Hz–1.0 MHz) and the transitional stage II (1.0–3.0 MHz) is attributed to shifting of the sample from the electronic to the ionic polarization stage, i.e., increasing the polarization and the dipole rotation speed of the molecules of the studied meteorite. At higher frequencies (> 3.0 MHz), the dipole rotation and the molecular mobility become faster and more complex than those at lower frequencies, and so the ϵ' decreases rapidly to very few

fractions (0.013). This explanation is consistent with that of Li et al. (2009) and Khater et al. (2019), whereby they attributed the steep decrease in ϵ' values to much lower values at higher f to the inability of the dipole rotation speed to follow the rotation speed of the applied AC. Mathematical modeling the ϵ' of the Gebel Kamil meteorite as a function of f enables its estimation by using a set of high-reliability models (R^2 of > 0.987) as shown in Figure 3. In contrast to the models obtained for σ , the constant values of these models decreased with an increase in f .

Dielectric Loss (ϵ'')

The ϵ'' is a function of ϵ' and f , and so it decreased by decreasing ϵ' and increasing f , but some peaks appeared at the low frequencies of stage I (50 Hz–1.0 MHz) and stage II (1.0–3.0 MHz) (Fig. 4). This can be attributed to the increase in f , which causes an increase in free electronic charges. The drop in ϵ'' values at these low frequencies stages was steep, reaching down to about 10% (0.019) at 3.0 MHz from the initial value at 50 Hz (1.194, Table 1). This can be attributed to the increase in f , which simplifies the ϵ'' behavior.

The relatively low σ and high ϵ' and ϵ'' values of the Gebel Kamil meteorite are attributed to its metallic composition with high amount of free ions, which are charged at high frequencies and start to rotate following the applied AC. At high frequencies, the electric charges are high and, therefore, the ability of electrons to flow increases, causing an increase in σ values, and the ability of ions to rotate as fast as changing the dipole frequency decreases, causing a reduction in the polarization parameters. However, at low frequencies, the electric charges are low and the rotation of the dipole frequency is slow; therefore, the ability of the electrons to flow is low and the ability of the ions to rotate is easier, i.e., the σ is low, while the dielectric parameters are high.

Modeling the ϵ'' values was based on the following mathematical models, which have high reliability ($R^2 \geq 0.895$), from which the ϵ'' can be estimated in terms of f , as shown in Figure 4. Similar to ϵ' , the constant values of the obtained models decreased by increasing the f due to decreasing the ability of the rotating ions to follow the applied dipole rotation.

CONCLUSIONS

From the present study, some conclusions can be drawn about the electric and dielectric characteristics of the Gebel Kamil meteorite.

1. The Gebel Kamil meteorite is a rustless and shiny, Ni-rich, iron meteorite (Ni = 20.4–22.3%, based on EDAX) with no impurities. The SEM imaging indicated that it is characterized by the common octahedral microstructure, which is a diagnostic feature of many iron meteorites.

2. Its electric conductivity (σ), dielectric constant (ϵ'), and dielectric loss (ϵ'') values are relatively high due to the presence of free charges that activate on applying AC frequency (f), in particular high-frequency values. The σ increases with increasing f (50 Hz–11.0 MHz), which causes the dielectric parameters to decrease.

3. The σ - f plot can be subdivided into three stages: (1) stage I (50 Hz–8.0 MHz) is an initial steady stage with a little bit increase in σ values; (2) stage II (8.0–10.5 MHz) is a transitional stage between stages I and II; and (3) stage III (10.5–11.0 MHz) is a steep stage with an abrupt increase in σ values.

4. The ϵ' - f and ϵ'' - f plots can be subdivided into three stages: (1) an initial steep stage with an abrupt decrease in dielectric values (50 Hz–1.0 MHz); (2) a transitional stage (1.0–3.0 MHz); and (3) a steady stage III with a little decrease in values (3.0–11.0 MHz).

5. Discrimination of the electric and dielectric behaviors of the Gebel Kamil meteorite into three stages is due to its richness in free charges (i.e., its high electronic activity). The electric and dielectric behaviors of the Gebel Kamil (increasing or decreasing as a function of f), besides its chemical composition, are considered diagnostic features of the studied Gebel Kamil meteorite.

ACKNOWLEDGMENTS

The author acknowledges Prof. Dr. John Carranza, Editor-in-Chief of NARR, the anonymous reviewers, Dr. Tomas Kohout, University of Helsinki, Finland, for revising the present manuscript and their comprehensive comments that greatly improved and reconstructed the manuscript quality.

FUNDING

Open access funding provided by The Science, Technology & Innovation Funding Authority (STDF) in cooperation with The Egyptian Knowledge Bank (EKB).

DECLARATIONS

Conflict of interest The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

OPEN ACCESS

This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

REFERENCES

- Bischoff, A., & Geiger, T. (1995). Meteorites from the Sahara: Find locations, shock classification, degree of weathering, and pairing. *Meteoritics*, 30(1), 113–122.
- Bland, P. A., Berry, F. J., Jull, A. J. T., Smith, T. B., Bevan, A. W. R., Cadogan, J. M., Sexton, A. S., Franchi, L. A., & Pillinger, C. T. (2002). ⁵⁷Fe Mössbauer spectroscopy studies of meteorites: Implications for weathering rates, meteorites flux, and early solar system processes. *Hyperfine Interactions*, 141(3), 481–494.
- Bland, P. A., Sexton, A., Jull, A. J. T., Bevan, A. W. R., Berry, F. J., Thornley, D., Astin, T., & Pillinger, C. T. (1998). Climate and rock weathering: A study of terrestrial age dated ordinary chondritic meteorites from hot desert regions. *Geochimica Et Cosmochimica Acta*, 62, 3169–3184.
- Britt, D. T., & Consolmagno, G. J. (2003). Stony meteorite porosities and densities: A review of the data through 2001. *Meteoritics & Planetary Science*, 38, 1161–1180.
- Britt, D. T., Yeomans, D., Housen, K., & Consolmagno, G. (2002). Asteroid density, porosity, and structure. In W. F. Bottke, A. Cellino, P. Paolicchi, & R. P. Binzel (Eds.), *Asteroids III* (pp. 485–500). Univ. of Arizona Press.
- Consolmagno, G. J., Bland, P. A., & Strait, M. M., (1999). Weathering and porosity: A preliminary SEM study of weathered meteorites. 30th Annual Lunar and Planetary Science Conference, abstract no. 1158.
- Consolmagno, G. J., Britt, D. T., & Macke, R. J. (2008a). The density and porosity of carbonaceous chondrites: A new look (abstract). *Meteoritics & Planetary Science*, 5038.
- Consolmagno, G. J., Britt, D. T., & Macke, R. J. (2008b). What density and porosity tell us about meteorites. *Lunar Planet. Sci.*, p. 1582 (XXXIX, LPI Contribution No. 1391, Abstract).
- Consolmagno, G. J., Britt, D. T., & Macke, R. J. (2008c). The significance of meteorite density and porosity. *Chemie Der Erde-Geochemistry*, 68, 1–30.
- Consolmagno, G. J., Macke, R. J., Rochette, P., Britt, D. T., & Gattacceca, J. (2006). Density, magnetic susceptibility, and the characterization of ordinary chondrite falls and showers. *Meteoritics & Planetary Science*, 41, 331–342.
- D'Orazio, M., Folco, L., Zeoli, A., & Cordier, C. (2011). Gebel Kamil: The iron meteorite that formed the Kamil crater (Egypt). *Meteoritics & Planetary Science*, 46(8), 1179–1196.
- Farrington, O. C. (1901). The structure of meteorites Part i. *The Journal of Geology*, 9(1), 51–66.
- Flynn, G. J., Consolmagno, G. J., Brown, P., & Macke, R. J. (2018). Physical properties of the stone meteorites: Implications for the properties of their parent bodies. *Chemie Der Erde*, 78, 269–298.
- Folco, L., Di Martino, M., El Barkooky, A., D'Orazio, M., Lethy, A., Urbini, S., Nicolosi, I., Hafez, M., Cordier, C., van Ginneken, M., Zeoli, A., Radwan, A. M., El Khrepy, S., El Gabry, M., Gomaa, M., Barakat, A. A., Serra, R., & El Sharkawi, M. (2010). The Kamil crater in Egypt. *Science*, 329, 804.
- Folco, L., Di Martino, M., El Barkooky, A., D'Orazio, M., Lethy, A., Urbini, S., Nicolosi, I., Hafez, M., Cordier, C., van Ginneken, M., Zeoli, A., Radwan, A. M., El Khrepy, S., El Gabry, M., Gomaa, M., Barakat, A. A., Serra, R., & El Sharkawi, M. (2011). Kamil crater (Egypt): Ground truth for small-scale meteorite impacts on Earth. *Geology*, 39, 179–182.
- Fry, C. (2013). 3D laser imaging and modelling of iron meteorites and tektites. M.Sc. thesis, Carleton University, Ottawa, Ontario, Canada.
- Fry, C., Samson, C., McCausland, P. J. A., Ralchenko, M., McLeod, T. K., & Goldstein, J. I. (2018). Iron meteorite bulk densities determined via 3-D laser imaging. *Meteoritics & Planetary Science*, 53(6), 1164–1178.
- Goldstein, J. I. (1965). The formation of the kamacite phase in metallic meteorites. *Journal of Geophysical Research*, 70(24), 6223–6232.
- Goldstein, J. I., Scott, E. R. D., & Chabot, N. L. (2009). Iron meteorites: Crystallization, thermal history, parent bodies, and origin. *Chemie Der Erde-Geochemistry*, 69(4), 293–325.
- Khater, G. A., Nabawy, B. S., Kang, J., & Mahmoud, M. A. (2019). Dielectric properties of basaltic glass and glass-ceramics: modeling and applications as insulators and semiconductors. *SILICON*, 11, 579–592.
- Khater, G. A., Nabawy, B. S., Kang, J., Yue, Y., & Mahmoud, M. A. (2020). Magnetic and electrical properties of glass and glass-ceramics based on weathered basalt. *SILICON*, 12, 2921–2940.
- Kohout, T., Kletetschka, G., Elbra, T., Adachi, T., & Mikula, V. (2008). Physical properties of meteorites—Applications in space missions to asteroids. *Meteoritics & Planetary Science*, 43(6), 1009–1020.
- Kremer, F., & Schonhals, A. (2003). *Broadband dielectric spectroscopy* (p. 718). Springer.

- Kukkonen, I. T., & Pesonen, L. J. (1983). Classification of meteorites by petrophysical methods. *Bull. Geol. Soc. Finland*, 55(2), 157–177.
- Li, H. M., Ra, C. H. H., Zhang, H., Yoo, W. J., Lee, K. W., & Kim, J. D. (2009). Frequency and temperature dependence of the dielectric properties of a PCB substrate for advanced packaging applications. *Journal of the Korean Physical Society*, 54(3), 1096–1099.
- Macke, R. J. (2010). Survey of meteorite physical properties: Density, porosity and magnetic susceptibility Ph D. Dissertation. University of Central Florida, Orlando, FL, 332 pp.
- Macke, R. J., Wiggins, S., Britt, D. T., Benedix, G. K., Bland, P. A., & Desert fire ball network team (2016). Density, porosity and magnetic susceptibility of the Murrili meteorite recovered by the desert fireball network. 79th Meteorit. Soc. Meet., 6147.
- Macke, R. J., Britt, D. T., & Consolmagno, G. J. (2010a). Analysis of systematic error in bead method measurements of meteorite bulk volume and density. *Planetary and Space Science*, 58, 421–426.
- Macke, R. J., Britt, D. T., & Consolmagno, G. J. (2011). Density, porosity, and magnetic susceptibility of achondritic meteorites. *Meteoritics & Planetary Science*, 46, 311–326.
- Macke, R. J., Consolmagno, G. J., & Britt, D. T. (2011). Density, porosity, and magnetic susceptibility of carbonaceous chondrites. *Meteoritics & Planetary Science*, 46, 1842–1862.
- Macke, R. J., Consolmagno, G. J., Britt, D. T., & Hutson, M. L. (2010b). Enstatite chondrite density, magnetic susceptibility, and porosity. *Meteoritics & Planetary Science*, 45(9), 1513–1526.
- Nabawy, B. S. (2018). Impacts of fossil anisotropy on the electric and permeability anisotropy of highly fossiliferous limestone: A case study. *Marine Geophysical Research*, 39, 537–550.
- Nabawy, B. S., & Rochette, P. (2016). A preliminary study on the electrical signatures of some iron and stony meteorites and their dependence on nickel content. *Acta Geophysica*, 64(5), 1942–1969.
- Norton, O. R. (1998). Rocks from space: Meteorites and meteorite hunters. Mountain Press. ISBN 0–87842–373–7.
- Norton, O. R. (2008). *Field guide to meteors and meteorites patrick moore's practical astronomy series* (pp. 75–111). Springer.
- Ostrowski, D., & Bryson, K. (2019). The physical properties of meteorites. *Planetary and Space Science*, 165, 148–178.
- Piqué, J. L., & Trigo-Rodríguez, J. M. (2004). Nuestra historia en los meteoritos. El sistema solar: Nuestro pequeño rincón en la vía láctea. Universitat Jaume I. p. 75. ISBN 978–8480214667.
- Scott, E. R. D. (2013). Handbook of iron meteorites by Vagn F. Buchwald, 1975: Electronic edition. *Meteoritics & Planetary Science*, 48, 2608.
- Scott, E. R. D., & Chabot, N. L. (2009). Iron meteorites: Crystallization, thermal history, parent bodies, and origin. *Chemie Der Erde*, 69, 293–325.
- Stelzner, T. K., Heide, A., Bischoff, D., Weber, P., Scherer, L., Schultz, M., Happel, W., Schron, W., Neupert, U., Michel, R., Clayton, R. N., Mayeda, T. K., Bonani, G., Haidas, I., Ivy-Ochs, S., & Suter, M. (1999). An interdisciplinary study of weathering effects in ordinary chondrites from the Ačfer region Algeria. *Meteoritics & Planetary Science*, 34(5), 787–794. <https://doi.org/10.1111/j.1945-5100.1999.tb01391.x>.
- Tehro, M., Pesonen, L. J., Kukkonen, I. T., & Bukovanská, M. (1993). The petrophysical classification of meteorites. *Studia Geophysica Et Geodaetica.*, 37, 65–82.
- Verma, H. C., & Tripathi, R. P. (2004). Anomalous Mössbauer parameters in the second generation regolith Ghubara meteorite. *Meteoritics & Planetary Science*, 39(10), 1755–1759.
- Welten, K. C. (1999). Concentrations of siderophile elements in nonmagnetic fractions of Antarctic H and L chondrites: A quantitative approach on weathering effects. *Meteoritics & Planetary Science*, 34(2), 259–270.