

Composition-based magnetic modeling of iron-rich planetesimals: application to the Hoba meteoroid parent body

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Abstract. In this study, we apply the Savić–Kašanin (SK) semi-empirical theory to estimate the magnetic properties of the Hoba meteoroid parent body. Using a Python-based SK calculator, the total magnetic moment was derived from the meteoroid’s measured composition (82.4 wt% Fe, 16.76 wt% Ni). The analysis constrains the magnetic pole separation to $\delta \leq 500$ km, indicating a parent body significantly smaller than Earth. Thermodynamic considerations are included as supporting physical constraints on density and volume, providing insight into the dense iron-rich nature of the body. The results are discussed in the context of paleomagnetic data from iron meteorites and classical dynamo scaling laws. This work demonstrates that the SK theory provides a coherent framework linking composition, magnetic properties, and spatial scale of small differentiated bodies, offering a complementary perspective to conventional dynamo-based interpretations.

Key words: Savić–Kašanin theory, meteoroid parent body, magnetic moment

1 Introduction

Understanding the origin and evolution of magnetic fields in small celestial bodies remains a central problem in planetary science and cosmochemistry (Фесенков, 1953; Safronov, 1972; Vdovichenko et al., 2025). Paleomagnetic studies of meteorites have provided compelling evidence that several differentiated planetesimals generated internal magnetic fields early in Solar System history. These magnetic records offer unique constraints on thermal evolution, core formation, and differentiation processes in early-formed bodies.

Modern models of planetesimal formation describe growth through gravitational accretion within protoplanetary disks, involving dust coagulation, streaming instability, and runaway growth. Once sufficiently massive, differentiated bodies may develop metallic cores capable of sustaining convective dynamos. Numerical dynamo scaling laws successfully reproduce magnetic field strengths for large planetary bodies and, in some cases, for differentiated planetesimals. However, these models primarily rely on fluid motion, rotation rate, and thermal convection parameters.

In parallel with dynamo-based approaches, alternative semi-empirical frameworks have been proposed to relate magnetic properties directly to bulk composition and thermodynamic state. One such framework is the Savić–Kašanin (SK) theory (Savić, Kašanin, 1965; Savić, 1981) originally developed to describe material behavior under high pressure and subsequently extended to planetary-scale magnetic properties. Within this formulation, magnetic characteristics are derived from elemental composition and macroscopic state variables, providing a complementary perspective to convection-driven dynamo theory.

The distinction between dynamo-generated fields and remanent magnetization recorded in solid metallic phases is particularly relevant for iron meteorites. Fe–Ni alloys, including taenite and kamacite phases, are capable of preserving ancient magnetic signals, enabling reconstruction of parent body

magnetic environments. Therefore, a framework that directly links composition to magnetic parameters may provide additional insight into the magnetic scaling behavior of small iron-rich bodies.

The Hoba meteorite, the largest known single-fragment iron meteorite preserved on Earth, offers a compelling case study. Its well-characterized iron-nickel composition (Luyten, 1929) provides a direct input for composition-based magnetic modeling. While classical dynamo theory describes magnetic field generation through core convection, the SK framework allows one to estimate bulk magnetic properties directly from compositional data, enabling an independent scaling analysis (Nikolić, 2023).

In this study, we apply the SK theory to estimate the magnetic dipole moment, surface magnetic field strength, and pole-to-pole separation of the Hoba parent body. These parameters are then interpreted in the broader context of differentiated planetesimal evolution. Thermodynamic considerations are used in a constrained and complementary manner to interpret equilibrium conditions associated with condensation and differentiation, without replacing gravitational accretion theory as the primary mechanism of mass assembly.

By applying the SK approach within the context of contemporary dynamo theory, meteoritic paleomagnetism, and planetesimal formation models, this work aims to explore whether composition-based magnetic scaling can provide additional constraints on the physical properties of small iron-rich celestial bodies. The results contribute to ongoing efforts to combine compositional, magnetic, and thermodynamic perspectives in understanding early Solar System evolution.

2 Methods

The Savić-Kaşanin (SK) theory provides a semi-empirical framework for estimating the magnetic properties of small differentiated bodies from their chemical composition and physical parameters. It allows the calculation of total magnetic moment and surface field strength without assuming fluid convection as in large-body dynamos.

A Python-based magnetic calculator was developed for this study (available at [GitHub](#)), implementing the following assumptions:

1. The Hoba parent body has the same Fe (82.4 wt%) and Ni (16.76 wt%) fractions as a meteorite. Contributions from other elements < 1 wt% are neglected.
2. The body is spherically shaped and differentiated, with a metallic core.
3. The total mass is approximately $1.6 \cdot 10^{25}$ g, which is consistent with the SK theory for sustaining a magnetic field.

Note that software was developed to estimate the magnetic contribution of iron in the case of the Hoba meteorite. The calculations are based on the weight fraction of iron in the meteorite (82.4 wt%), the relative atomic mass of iron ($A_r(\text{Fe}) = 55.845$), the molar volume ($V_{\text{mol}}(\text{Fe}) = 7.09 \text{ cm}^3$), considering the electronic configuration of iron ($1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^6$), and appropriate values for the ionization energies of each shell (the first ionization energy, $E_{i,1} = 7.90 \text{ eV}$). The program probes the ionization energies required to ionize the electronic shells and subsequently calculates the magnetic contribution of iron.

To apply the software to another element, the corresponding parameters must be introduced. In the case of the Hoba meteorite, the second element of interest is nickel. For nickel, the relevant parameters are weight fraction 16.76 wt%, $A_r(\text{Ni}) = 58.69$, the molar volume ($V_{\text{mol}}(\text{Ni}) = 6.59 \text{ cm}^3$), considering the electronic configuration of nickel ($1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^8$), and appropriate values for the ionization energies of each shell (the first ionization energy, $E_{i,1} = 7.64 \text{ eV}$).

The total magnetic moment, L_{total} , was calculated separately for Fe and Ni and then summed, Eq. (1):

$$L_{\text{total}} = L_{\text{Fe}} + L_{\text{Ni}}. \quad (1)$$

The pole-to-pole separation, δ , was estimated using the SK relations, relating the total magnetic moment and the magnetic pole “charge”, μ , Eq. (2):

$$\mu \approx \frac{L_{\text{total}}}{2\delta}, \quad (2)$$

with the SK constraint $\mu > \frac{L_{\text{total}}}{2}$. By evaluating the maximum δ consistent with this inequality, the analysis determines the largest physically plausible radius for the Hoba parent body.

The magnetic pole separation, d , was estimated by evaluating the surface field along the spherical body and identifying maximum positive and negative vertical components, corresponding to the approximate north and south magnetic poles. The pole-to-pole distance was then calculated as the arc length along the sphere, Eq. (3):

$$d = R \cdot \theta, \quad (3)$$

where θ is the angular separation between the poles.

Thermodynamic considerations were applied only as physical constraints to illustrate that small, dense iron-nickel bodies are consistent with low-pressure, low-temperature formation environments. These constraints complement, rather than replace, classical gravitational accretion theory as the primary mechanism of mass assembly.

3 Results and discussion

3.1 Magnetic properties derived through the SK theory

The total magnetic moment L_{total} of the Hoba parent body was calculated using the Python-based SK calculator, based solely on its measured composition (82.4 wt% Fe and 16.76 wt% Ni). Individual contributions from Fe and Ni are $\text{Fe} \approx 2.7 \cdot 10^{21} \text{ A} \cdot \text{m}^2$ and $\text{Ni} \approx 0.5 \cdot 10^{21} \text{ A} \cdot \text{m}^2$. Summing these contributions gives a total magnetic moment consistent with predictions from the SK theoretical framework.

To estimate the spatial configuration of the magnetic field, the magnetic pole separation δ was determined using the SK formalism, applying the constraint on the magnetic pole ‘‘charge’’ μ , where $\mu > \frac{L_{\text{total}}}{2}$. Using this relation in combination with the dipole approximation, the analysis demonstrates that the maximum radius of the Hoba parent body, consistent with these constraints, is $R \approx 500$ km. This corresponds to a pole-to-pole separation $\delta \leq 500$ km, establishing that the Hoba parent body was much smaller than Earth, whose pole-to-pole separation is $\sim 12\,700$ km. These results provide a physically meaningful estimate of the body’s spatial scale without relying on assumptions about the time evolution of the magnetic field.

In the SK theory, the total magnetic moment L_{total} is related to the magnetic pole ‘‘charge’’ μ . For smaller bodies like meteoroids, this relation implies a reduced pole-to-pole separation δ compared with larger celestial bodies. This provides a theoretical basis for the small δ estimated for the Hoba parent body.

The small volume of the Hoba parent body, combined with its compact pole-to-pole separation and high iron-nickel content, indicates a dense metallic structure consistent with formation under low-pressure, low-temperature conditions, as reported for meteoroid parent bodies (Anders, 1964; Urey, Craig, 1953). These constraints provide a physically meaningful estimate of the body’s spatial scale and support the plausibility of coherent internal magnetic structures in even small differentiated planetesimals, without replacing standard gravitational accretion theory.

These results are consistent with the general trend that small, differentiated iron-rich bodies can sustain measurable magnetic structures, as suggested by paleomagnetic studies of other iron meteorites (Weiss et al., 2010; Nichols et al., 2020; Weiss, Elkins-Tanton, 2013).

3.2 Comparison with observational data and physical interpretation

Paleomagnetic measurements of iron meteorites provide observational data for assessing the magnetic properties of small differentiated bodies. Studies indicate remanent magnetic fields in the range of 10^{-2} – 10^{-1} T (Weiss et al., 2010; Nichols et al., 2020), consistent with the composition-based estimates obtained for the Hoba parent body using the SK theory. These results support the plausibility that even small iron-nickel-rich planetesimals can retain coherent internal magnetic structures over geological timescales.

Classical dynamo scaling laws (Christensen, Aubert, 2006) predict that convective dynamos in bodies with radii smaller than ~ 1000 km produce weaker fields, aligning with the reduced spatial scale and estimated pole-to-pole separation inferred for Hoba. This correspondence suggests that the compact magnetic configuration derived from the SK theory is physically reasonable for a low-volume, high-density iron-nickel-rich body.

Further, consideration of simple thermodynamic relations can provide insight into the gas behavior

during the formation of meteoroids in metal-rich regions of a protoplanetary disk. Specifically, the constancy of the ratio of pressure to volume and the relationship between the number of moles and temperature via the universal gas constant R can be used to estimate relevant thermodynamic conditions. In this discussion, non-ideal effects and the contribution of solid metals to the gas law are neglected in order to emphasize the principal trends.

If the thermodynamic parameters (pressure, volume, and temperature) attain magnitudes higher than those characteristic of ideal steady-state conditions, the number of moles, n , must correspondingly decrease relative to steady-state expectations. Recall that the number of moles can be expressed as the ratio of the total mass to the averaged molar mass of the celestial body under consideration. Accordingly, the elemental composition of the celestial bodies (such as stars or planets) should reflect an averaged chemical composition that does not overestimate the contribution of light elements (those with molar mass less than that of iron). Literature data confirm this assumption: the Sun consists predominantly of hydrogen (~ 71 wt%) and helium (~ 27 wt%), while Earth is largely composed of oxygen (~ 46 wt%), silicon (~ 28 wt%), and aluminum (~ 8 wt%).

Although the SK theory does not explicitly address meteoroid formation, applying its framework allows important conclusions to be drawn. The Hoba parent body, according to literature data, formed under low-temperature, low-pressure conditions and also exhibited a small volume (as is shown earlier in this study). Considering the relationship between thermodynamic parameters, a low pressure and low temperature implies a high value of the averaged molar mass. This, in turn, suggests a composition dominated by heavier elements. Indeed, the Hoba meteorite is composed primarily of iron (~ 82 wt%) and nickel (~ 17 wt%), consistent with this expectation.

Moreover, if the number of moles and the averaged molar mass are both high, as in the case of the Hoba meteoroid parent body, the total mass must also be high relative to bodies with low number of moles and large volume (e.g., planets or stars). Given the direct proportionality between mass and volume, this results in a high density. Comparison with elemental densities (Table 1) confirms that iron and nickel exhibit the highest densities among the considered elements, which is consistent with the observed properties of the Hoba parent body.

Table 1. Density of selected chemical elements

Element	Density [g/cm ³]
H	0.09
He	0.21
O	1.50
Si	2.33
Al	2.70
Fe	7.78
Ni	8.90

Consequently, the small pole-to-pole separation and high density of the Hoba parent body support formation in metal-rich regions of the protoplanetary disk under low-pressure, low-temperature conditions. The relationship between mass, volume, and density ($V = \frac{m}{\rho}$) provides further insight into this high-density structure. Table 1 summarizes the densities of selected elements, illustrating how the iron-nickel composition leads to significantly higher bulk density than bodies composed of lighter elements such as hydrogen, helium, oxygen, or silicon.

Since the SK magnetic model does not explicitly incorporate pressure in its mathematical basis, it shows good agreement with experimental data. The results suggest that the formalism can be applied to materials formed under a variety of conditions, not exclusively high-pressure environments. These considerations reinforce the conclusion that meteoroid parent bodies experienced distinct thermodynamic and compositional conditions compared with planets or stars, consistent with their small volume, high density, and metal-rich chemistry.

Thus, the SK theory provides a physically consistent framework linking elemental composition, magnetic moment, and spatial scale, offering a composition-based perspective complementary to conventional dynamo interpretations. The inferred magnetic properties are sensitive to the assumed total mass and spherical geometry of the parent body; variations in these parameters would adjust the estimated

radius. Moreover, the SK formalism does not explicitly account for convective dynamo processes; thus, the results should be interpreted as upper-limit, composition-based estimates rather than precise dynamo simulations.

4 Conclusions

The application of the Savić–Kašanin semi-empirical framework provides model-dependent estimates of the total magnetic moment and spatial configuration of the Hoba parent body. Using the measured Fe–Ni composition, the analysis constrains the magnetic pole separation to $\delta \leq 500$ km, consistent with a small, dense, differentiated iron-rich body. These results provide a physically meaningful estimate of spatial scale and internal magnetic configuration without relying on assumptions about the time evolution of the magnetic field.

While the inferred values are sensitive to the assumed total mass and spherical geometry, the study demonstrates that composition-based magnetic scaling can complement conventional dynamo-based approaches for understanding the magnetic properties of meteoritic parent bodies. The framework offers a coherent link between elemental composition, magnetic moment, and body size, highlighting how even small differentiated planetesimals may retain coherent internal magnetization despite their limited volume.

Future work should include systematic sensitivity analyses, application to additional iron meteorites, and integration with paleomagnetic and thermodynamic data to further evaluate the robustness and general applicability of the SK framework to small differentiated objects in the early Solar System.

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