



Possible risk resulting from the recent decay of the dipolar component of the terrestrial magnetic field

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Abstract

In this study, we investigated the geomagnetic ground observatory data from 1980 to 2011 collected from World Data Center from 134 stations. To analyze the data we have applied spherical harmonic decomposition to obtain components associated with the Earth's main magnetic field and to calculate how the Earth's dipole was varying in the aforementioned recent 31-year period. There is a visible ~2.3% decay of the dipole magnetic field of the Earth. We note that the present-day value of the magnetic dipole intensity is the lowest one in the history of modern civilization and that further drop of this value may pose a risk for different domains of our life.

Keywords Geomagnetic observatory data · Geomagnetic field · Earth's dipole · Earth's main magnetic field · Earth's dipole variations

Introduction

The Earth's magnetic field is an essential part of the geosystem, which protects mankind from the solar wind (Reshetnyak and Pavlov 2016). However, the geomagnetic field is constantly decaying for the last ca. 2 ky. Virtual axial dipole moment dropped by ca. 30% from the advent of our era (Laj et al. 2002). Some research (Brown et al. 2018; Finlay et al. 2016) gives a decay rate of ~9% since 1840. Other investigations (Davies and Constable 2020; Opdyke and Mejia 2004) argued that such an instability may herald forthcoming excursion or even inversion (Nowaczyk et al. 2012; Olson and Amit 2006; Reshetnyak and Pavlov 2016; Sokoloff 2017). The latter may take place abruptly, as fast as within a few hundreds of years, as in the case of Brunhes/Matuyama reversal (Sagnotti et al. 2014). An opposite view was presented by Brown et al. (2018), who constructed a field evolution model for two most recent excursions and concluded that the current morphology of the field is not

of the type leading to a significant excursion, because there are no reversed flux patches in both hemispheres at the core–mantle boundary and the field weakening is localized. This suggests that currently, the geomagnetic field is not reversing.

As noted by research (Bloxham 1986), if the current rate of decay of the Earth's dipole component is maintained, it will vanish in less than 2000 years. Also, it was noted (Finlay et al. 2016) that if the mean decay rate between 1840 and 2010 of 16 nT yr^{-1} would be maintained, the axial dipole would reach zero within 1900 years. On the other hand, strength of the time-averaged field at the millennial timescale is still by 40% weaker than the present-day field (Wang et al. 2015). It seems, therefore, that the intensity of the dipole field is currently far from reaching a critical, near-zero value, characteristic for geomagnetic inversion or excursion (Channell et al. 2000; Clement and Kent 1985; Mazaud et al. 1989).

In this paper we quickly verify, using simple calculations, that the decaying trend is indeed sustained during the last decades. We compared our results with outcomes from the well-established global models of the geomagnetic field, i.e., COV-OBS (Gillet et al. 2015) and IGRF (Thébault et al. 2015). In all three cases, the results are very similar, confirming the decaying trend of the geomagnetic dipolar moment.

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Methodology

The observed geomagnetic field is a sum of internal and external parts which can be described as $\mathbf{B} = \mathbf{B}_i + \mathbf{B}_e$ (Gillet et al. 2013). Both of these parts are potential fields: $\mathbf{B}_{i,e} = -\text{grad}(V_{i,e})$ (Campuzano et al. 2015; Gillet et al. 2013; Olson and Amit 2006). The internal part of the geomagnetic field can be decomposed into a sum of spherical harmonics (Gillet et al. 2013) with radially dependent coefficients (1):

$$V_i(r, \theta, \varphi) = a \sum_{n=1}^{N_i} \left(\frac{a}{r}\right)^{n+1} \sum_{m=0}^n [g_n^m \cos m\varphi + h_n^m \sin m\varphi] P_{nm}(\cos \theta), \quad (1)$$

where $a = 6371$ km is the mean radius of the Earth, P_{nm} are associated Legendre functions of degree n and order m , and $\{g_n^m, h_n^m\}$ are the Gauss coefficients. The external part of the geomagnetic field can be described in a similar way (Schmucker 1999), but with a different radial dependence of the coefficients as in (2):

$$V_e(r, \theta, \varphi) = a \sum_{n=1}^{N_e} \left(\frac{a}{r}\right)^{n+1} \sum_{m=0}^n [g_n^m \cos m\varphi + h_n^m \sin m\varphi] P_{nm}(\cos \theta) \quad (2)$$

For calculating the Gauss coefficients we had to solve an Eq. (3):

$$\mathbf{m} = \mathbf{A}^{-1} \mathbf{d}, \quad (3)$$

where \mathbf{d} is a vector with observed values of the geomagnetic field, \mathbf{m} is a vector of Gauss coefficients and \mathbf{A} is a matrix with Legendre functions and coefficients. Because the \mathbf{A} matrix is usually not quadratic, it is more convenient to express Eq. (3) in the following form (4):

$$\mathbf{m} = (\mathbf{A}^T \mathbf{A})^{-1} (\mathbf{A}^T \mathbf{d}). \quad (4)$$

Since the quality of geomagnetic data is varying in time and space, we utilized the IGRF model to calculate diagonal weight matrix $\mathbf{W} = 1/\sigma^2 * \mathbf{1}$, where $\sigma = \text{rms}(\mathbf{d} - \mathbf{A}\mathbf{p})$, and \mathbf{p} is a vector with predicted data from the IGRF model. This allows to obtain the final expression (5) for the Gauss coefficients:

$$\mathbf{m} = (\mathbf{A}^T \mathbf{W} \mathbf{A})^{-1} (\mathbf{A}^T \mathbf{W} \mathbf{d}). \quad (5)$$

After the full \mathbf{m} vector is obtained, one can proceed to extract only the dipolar component which is a sum of the terms g_1^0 , g_1^1 and h_1^1 (Campuzano et al. 2015; Olson and Amit 2006).

Data processing

We were analyzing the geomagnetic ground observatory data from 1980 to 2011 collected from World Data Center (WDC) for Geomagnetism (Edinburgh) from 134 stations (locations are shown in Fig. 1).

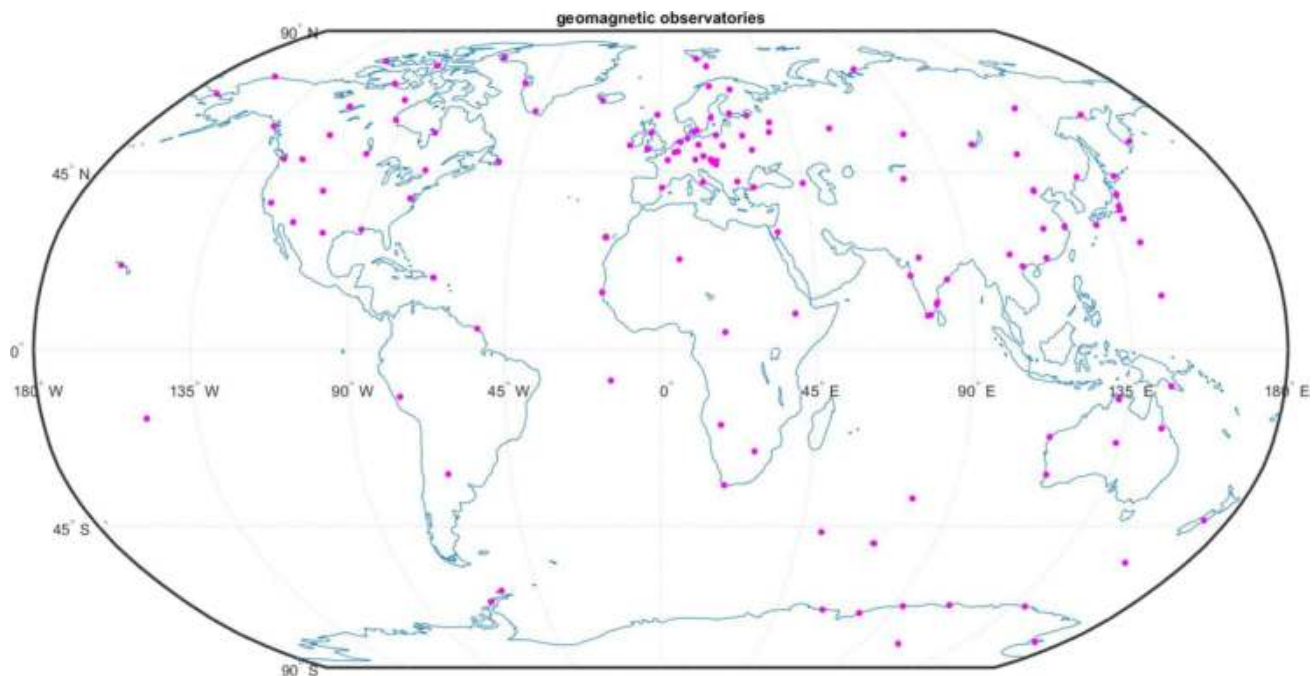


Fig. 1 Distribution of the geomagnetic observatories from which the data were collected

For data analysis, we have applied the spherical harmonics decomposition to separate the Earth’s main magnetic field from the external (solar) sources and to calculate variations of the Earth’s dipole in the period from 1980 to 2011 (Campuzano et al. 2015; Gillet et al. 2013; Schmucker 1999). We have decomposed the internal part of the geomagnetic field, using Eq. (1), into a sum of spherical harmonics (Gillet et al. 2015) with radially dependent coefficients. As typically done in the literature in our method we assumed $N_i = 6$ and $N_e = 1$.

We have calculated the strength of the dipole moment \mathbf{M} using Eq. (6) (Olson and Amit 2006):

$$\mathbf{M} = \frac{4\pi r^3}{\mu_0} * (g_1^0 \mathbf{x} + g_1^1 \mathbf{y} + h_1^1 \mathbf{z}), \tag{6}$$

where $\mu_0 = 4\pi * 10^{-7}$ H/m is the free-space magnetic permeability, and $(\mathbf{x}, \mathbf{y}, \mathbf{z})$ are Cartesian unit vectors with the origin of the Cartesian system at the Earth’s center. Variations of these Gauss coefficients and the dipole moment from 1980 to 2011 are presented in Figs. 2 and 3.

The next step in our research was to calculate location of the north geomagnetic pole (NGP) and its variations in time. For that purpose, we have used Eq. (7) (Olson and Amit 2006) to calculate the colatitude and east longitude of the NGP,

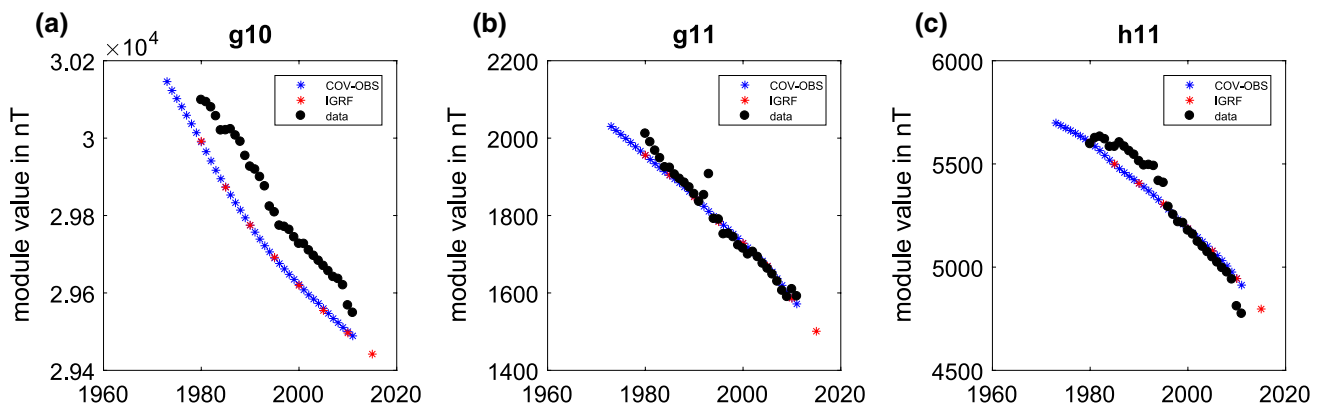


Fig. 2 Variations of the absolute values of Gauss coefficients **a** g_1^0 , **b** g_1^1 and **c** h_1^1 from the global COV-OBS and IGRF models and raw data from observatories

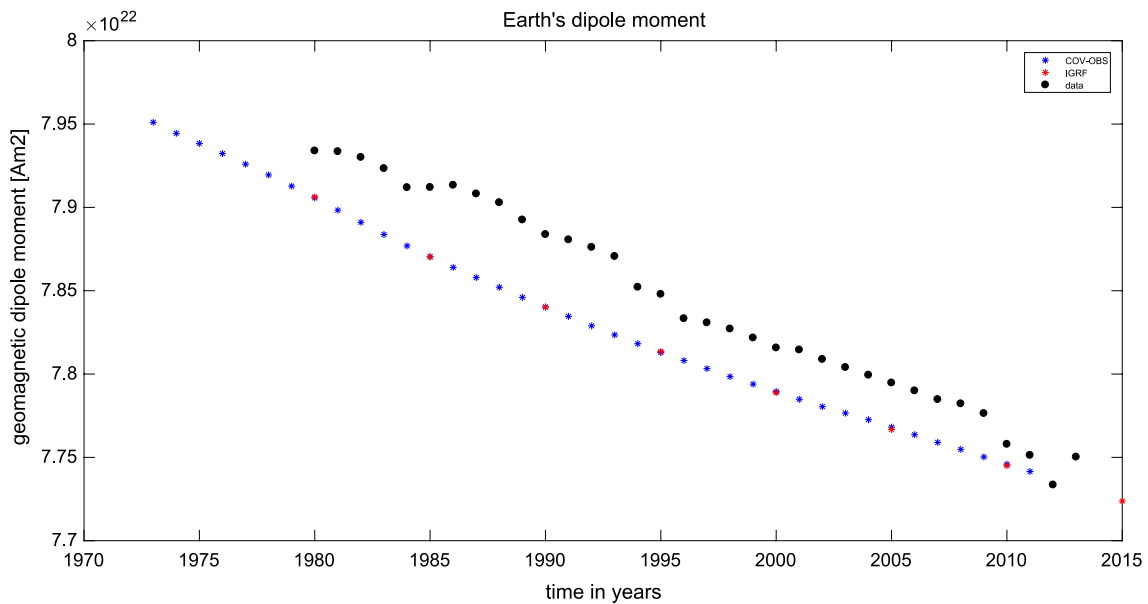


Fig. 3 Variations of the dipole moment from the global COV-OBS and IGRF models and raw data from observatories

$$\begin{aligned}\varphi_N &= \tan^{-1} \left(\frac{h_1^1}{g_1^1} \right), \\ \theta_N &= \cos^{-1} \left(-\frac{g_1^0}{g} \right),\end{aligned}\quad (7)$$

where $g = \sqrt{(g_1^0)^2 + (g_1^1)^2 + (g_1^2)^2}$. Variations of the position of NGP in a time range from 1980 to 2011 are shown in Fig. 4.

Results

Results obtained in our study clearly demonstrate consequent geomagnetic dipole decay since 1980, when the value of dipole moment was 2.3% higher than today. However, geomagnetic dipole is still above paleomagnetic field averaged for a millennial timescale (Wang et al. 2015), and the present-day value of $7.75 \cdot 10^{22}$ [Am²] is most probably the lowest one in the history of the modern civilization. Regardless of whether the current geomagnetic dipole decay will continue or will recover (as suggested in research of Brown et al. 2018), the current level of the dipole will pose a danger for our high-tech civilization.

Such a low level of geomagnetic field has various consequences for different aspects of our lives; for example, the increased flux of solar wind particles entering the magnetosphere and ionospheres of our planet has a damaging effect on biological organisms. The particles, breaking through the weaker geomagnetic shield, may be harmful to humans themselves, increasing exposure to cosmic radiation. Moreover, a weaker geomagnetic field strongly influences the radio satellite communication, as the ionosphere transparency for radio waves

is strongly dependent on the concentration of electrons. As the electron concentration increases, the critical frequency for penetration of radio waves increases as a square root of the concentration. Furthermore, the intensity of plasma instabilities associated with the Pedersen currents in the ionosphere increases with a weakening of the geomagnetic field; hence, those instabilities become more violent in weaker fields. The declining field may fall below a limit, which could be potentially dangerous for our electronics and electric supply infrastructure. Examples experienced so far involve the geomagnetic storm that struck the Earth on March 13 in 1989, causing a nine-hour outage of Hydro-Québec's electricity transmission system. Much earlier, in 1859, a powerful geomagnetic storm seriously damaged the telegraph systems, as at that time the global electrical grid was much less developed than nowadays; recently in 2012, a storm of similar magnitude passed very near the Earth (Liu et al. 2014).

We would like to put attention that further progress of the phenomenon of field decay, otherwise beyond our control, may increase the risk for many domains of our life, regardless of whether the observed decay will continue or follows a natural dipole oscillation within the actual polarity zone. In fact, there is no need for geomagnetic field to decay completely to allow the solar particles for the increasingly destructive invasion to our living space, particularly affecting electrical power grids and satellite-based communications.

Conclusions

Variations of the geomagnetic dipole are visible from the presented graphs. A drop of 2.31% in the strength of the geomagnetic dipole from 1980 to 2011 is clearly visible. This is a sign of an enhanced decay of the geomagnetic

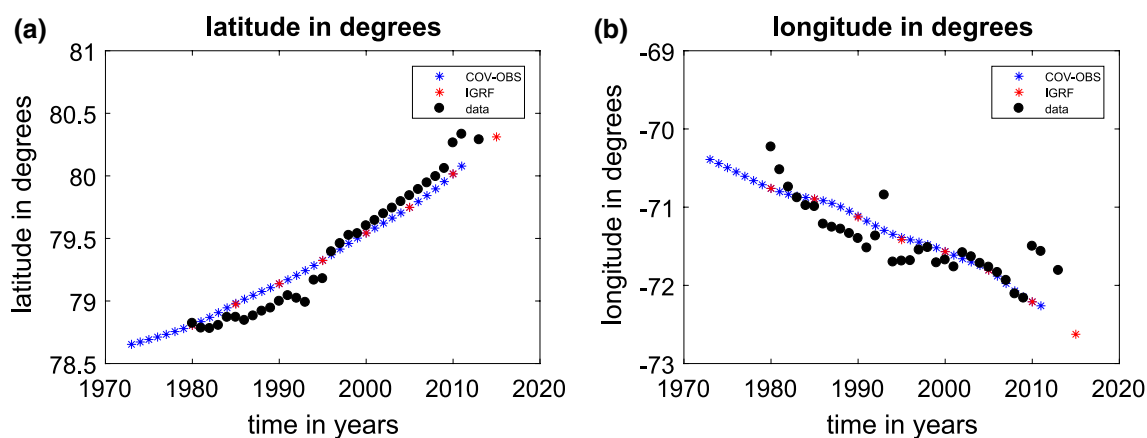


Fig. 4 Variations of the position of NGP, variations of **a** latitude and **b** longitude, based on global COV-OBS and IGRF models and raw data from observatories

field in comparison with a 10% drop over the entire past millennium reported in other studies. Such a pace of the geomagnetic field decay may lead to a decrease in the magnitude of the geomagnetic field down to a level that can be potentially dangerous for our technology and civilization.

The main aim of this paper was to point out that as the civilization is becoming more and more advanced, it simultaneously becomes more prone to threats resulting from strong magnetic storms, especially that the magnetic shield of our planet is weakening. Therefore, solar coronal mass ejections such as those which led to the Quebec blackout of 1989 or the 1859 geomagnetic storm are likely to have much more serious consequences for our lives in the future. Among the possible consequences, particular attention should be paid to the risk associated with the occurrence of disturbances in radio satellite communication, local electric outages, as well as the impact of increased cosmic radiation on human health.

Wanting or not, we are gradually losing our magnetic shield with uncertain consequences for ourselves. That's why we suggest continuous monitoring of changes in the Earth's dipole with the conjunction of solar coronal mass ejections and cosmic radiation activity. Knowing possible threats will allow us as a civilization to put an effort to minimize the risk and adapt to forthcoming changes.

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Author contributions All the authors contributed to the results and writing the paper. AB was more involved in the design and conducting the research, wrote the first draft, and made figures. ML initiated the project, motivated studies, participated in manuscript writing, and formulated conclusions. KM supervised the geomagnetic data analysis and participated in manuscript writing.

Data availability All data were collected from WDC for Geomagnetism (Edinburgh).

Code availability Custom code.

Compliance with ethical standards

Conflict of interest The authors declare no competing interests.

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References

- Bloxham J (1986) Evidence for asymmetry and fluctuation. *Nature* 322:13–14
- Brown M, Korte M, Holme R, Wardinski I, Gunnarson S (2018) Earth's magnetic field is probably not reversing. *Proc Natl Acad Sci* 115(20):201722110
- Campuzano SA, Pavón-Carrasco FJ, Osete ML (2015) Non-dipole and regional effects on the geomagnetic dipole moment estimation. *Pure Appl Geophys* 172(1):91–107. <https://doi.org/10.1007/s00024-014-0919-3>
- Channell JET, Stoner JS, Hoddel DA, Charles CD (2000) Geomagnetic intensity for the last 100 kyr from the sub-Antarctic South Atlantic: a tool for inter-hemispheric correlation. *Earth Planet Sci Lett* 175:145–160. [https://doi.org/10.1016/S0012-821X\(99\)00285-X](https://doi.org/10.1016/S0012-821X(99)00285-X)
- Clement BM, Kent DV (1985) A comparison of two sequential geomagnetic polarity transitions (upper Olduvai and lower Jaramillo) from the Southern Hemisphere. *Phys Earth Planet Int* 39:301–313. <https://doi.org/10.7916/D8NP2DXN>
- Davies CJ, Constable CG (2020) Rapid geomagnetic changes inferred from Earth observations and numerical simulations. *Nat Commun* 11:3371. <https://doi.org/10.1038/s41467-020-16888-0>
- Finlay CC, Aubert J, Gillet N (2016) Gyre-driven decay of the Earth's magnetic dipole. *Nat Commun*. <https://doi.org/10.1038/ncomms10422>
- Gillet N, Jault D, Finlay CC, Olsen N (2013) Stochastic modeling of the Earth's magnetic field: inversion for covariances over the observatory era. *Geochem Geophys Geosyst* 14(4):766–786. <https://doi.org/10.1002/ggge.20041>
- Gillet N, Barrois O, Finlay CC (2015) Stochastic forecasting of the geomagnetic field from the COV-OBS.x1 geomagnetic field model, and candidate models for IGRF-12. *Earth Planets Sp* 67:71. <https://doi.org/10.1186/s40623-015-0225-z>
- Laj C, Kissel MC, Mazaud A, Michel E, Muscheler R, Beer J (2002) Geomagnetic field intensity, North Atlantic deep water circulation, and atmospheric $\Delta^{14}\text{C}$ during the last 50 kyr. *Earth Planet Sci Lett* 200:179–192. [https://doi.org/10.1016/S0012-821X\(02\)00618-0](https://doi.org/10.1016/S0012-821X(02)00618-0)
- Liu Y, Luhmann J, Kajdič P et al (2014) Observations of an extreme storm in interplanetary space caused by successive coronal mass ejections. *Nat Commun* 5:3481. <https://doi.org/10.1038/ncomm54481>
- Mazaud A, Laj C, Bard E (1989) Phenomenological model for reversals of the geomagnetic field. In: Lowes FJ et al (eds) *Geomagnetism and paleomagnetism*, NATO ASI series C: mathematical and physical sciences, vol 261, pp 205–214
- Nowaczyk NR, Arz HW, Frank U, Kind J, Plessen B (2012) Dynamics of the Laschamp geomagnetic excursion from Black Sea sediments. *Earth Planet Sci Lett* 351–352:54–69. <https://doi.org/10.1016/j.epsl.2012.06.050>

- Olson P, Amit H (2006) Changes in Earth's dipole. *Naturwissenschaften* 93(11):519–542. <https://doi.org/10.1007/s00114-006-0138-6>
- Opdyke ND, Mejia V (2004) Earth's magnetic field. In: Channell J, et al. (eds) *Timescales of the Paleomagnetic Field*. Geophys. Monogr. Ser., vol 145. AGU, Washington, DC, pp. 315–320. <https://doi.org/10.1029/145GM24>
- Reshetnyak MY, Pavlov VE (2016) Evolution of the dipole geomagnetic field. *Observ Models Geomagn Aeron* 56(1):110–124. <https://doi.org/10.1134/S0016793215060122>
- Sagnotti L, Scardia G, Giaccio B, Liddicoat JC, Nomade S, Renne PR, Sprain CJ (2014) Extremely rapid directional change during the Matuyama-Bruhnes geomagnetic polarity reversal. *Geophys J Intern* 199:1110–1124. <https://doi.org/10.1093/gji/ggu287>
- Schmucker U (1999) A spherical harmonic analysis of solar daily variations in the years 1964–1965: response estimates and source fields for global induction—I. *Methods Geophys J Int* 136(2):439–454. <https://doi.org/10.1046/j.1365-246X.1999.00742.x>
- Sokoloff DD (2017) Earth's magnetic moment during geomagnetic reversals. *Izv Phys Solid Earth* 53(6):855–859. <https://doi.org/10.1134/S1069351317060064>
- Thébault E, Finlay CC, Beggan CD et al (2015) International geomagnetic reference field: the 12th generation. *Earth Planet Sp* 67:79. <https://doi.org/10.1186/s40623-015-0228-9>
- Wang H, Kent DV, Rochette P (2015) Weaker axially dipolar time-averaged paleomagnetic field based on multidomain-corrected paleointensities from Galapagos lavas. *PNAS*. <https://doi.org/10.1073/pnas.1505450112>