Space Sci Rev (2010) 155: 1–7
DOI 10.1007/s11214-010-9703-6

The Earth's Magnetic Field in the Space Age: An Introduction to Terrestrial Magnetism

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Received: 11 October 2010 / Accepted: 11 October 2010 / Published online: 4 November 2010

The series of papers presented in this issue of Space Science Research (reprinted as Volume 36 in the Space Science Series of ISSI) is the result of a fruitful workshop that took place at the International Space Science Institute (ISSI), in Bern, Switzerland, during the week of March 9–13, 2009. Focussing on the (still very broad) topic of Terrestrial Magnetism, this workshop was the last of a series of three that aimed to present, discuss and summarize recent advances in our understanding of magnetic fields in the solar system. The earlier workshops, on solar and on planetary magnetism, were held in January and September 2008

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and have already resulted in two similar collections of review papers published in Space Science Reviews (Vol. 144, 1–4, 2009; Vol. 152, 1–4, 2010) and reprinted in volumes 32 (Thompson et al. 2009) and 33 (Christensen et al. 2010a) of the ISSI book series. Various important aspects of the Earth's magnetic field were discussed at those meetings, and interested readers might want to consult the corresponding reviews, especially those addressing topics not or only partly covered in the present volume: current systems in magnetospheres and ionospheres (Baumjohann et al. 2010), induced magnetic fields in planets and moons (Saur et al. 2010), and the issue of separating magnetic fields of external origin from those of internal origin (Olsen et al. 2010a). The planetary magnetism volume also contains additional very relevant reviews, that discuss magnetic field measurements from space (Balogh 2010), crustal magnetism in a planetary perspective (Langlais et al. 2010), the relationship between thermal evolution and the ability of terrestrial planets to produce intrinsic magnetic fields (Breuer et al. 2010), dynamo numerical modelling (Wicht and Tilgner 2010; Christensen 2010), and laboratory dynamo experiments (Verhille et al. 2010). Readers interested in a more general overview of our current knowledge of the Earth's main magnetic field, might also want to consult Hulot et al. (2010a), before turning to the more specialized series of reviews included in this volume.

Terrestrial magnetism is hardly a new science: investigation of the Earth's magnetic field began in China (see e.g., Courtillot and Le Mouël 2007 for a historical account) and when it emerged that the magnetic field was useful for navigational purposes this quickly led to systematic direct measurements (see e.g., Jackson et al. 2000). This historical record, together with the possibility offered by magnetized rock samples to recover some information about the ancient and very ancient field (see e.g., Tauxe 2010), is what makes investigation of the Earth's magnetic field distinctly different from that of other planetary magnetic fields: Earth is the only planet for which very long time series of magnetic data are accessible.

However it is the advent of high precision magnetometry from space, initiated by the launch of the US *MAGSAT* mission in 1980, that has truly opened up a new era in the investigation of the Earth's magnetic field. As noted by Gubbins (2010) in the historical perspective opening the present series of reviews, *MAGSAT* provided the first high resolution maps of the field of internal origin, revealed the potential of the historical data accumulated so far, and prompted the production of the first field maps at the core surface as a function of time and their inversion in terms of flows at the top of the core (e.g., Bloxham et al. 1989). This was a crucial step towards better understanding the dynamics governing the core magnetic field. *MAGSAT* also prompted new ways of modelling and identifying the various sources of the field, leading to considerable progress in our understanding of the field of lithospheric origin (e.g. Langel and Hinze 1998). But *MAGSAT* operated only for nine months, and it was not until the launch of the very successful *Ørsted* (February 1999, Neubert et al. 2001) and *CHAMP* (July 2000, Reigber et al. 2002) satellites that similar, even higher quality data became available, providing additional opportunities for progress and setting the stage for what, we may hope, could eventually become the permanent observation of Earth's magnetic field from space. *Ørsted* has shown that the smallest scales of the core field evolve fast (Hulot et al. 2002), and *CHAMP* has revealed the potential of accumulating data at low altitude for mapping the lithospheric field (Maus et al. 2009). *CHAMP* also made possible much progress in our understanding of many other field sources, such as that of the ocean tides (Tyler et al. 2003). The scientific motivation for permanently monitoring the field from space is now very strong.

After more than ten years of good and faithful service, *CHAMP* just re-entered Earth's atmosphere on September 19, 2010. Only *Ørsted* remains in orbit (at a higher altitude and now with reduced capabilities for providing data). This is a remarkable achievement, considering the nominal lifetimes of *Ørsted* (14 months) and *CHAMP* (4.5 years). Fortunately, relief is already in sight. Selected in 2004 by the European Space Agency (ESA), the three-satellite mission *Swarm*, now scheduled for launch in mid-2012, will ensure a minimum of 4.5 years of further magnetic monitoring. It will also provide even more scientific opportunities, thanks, in particular, to a new constellation design (Friis-Christensen et al. 2006). At the end of what is now known as the *International Decade of Geopotential Field Research* and on the eve of what may become the *Swarm* decade, organizing a workshop on terrestrial magnetism was clearly very appropriate.

It should be stressed that the past decade has also seen considerable progress in many other aspects of terrestrial magnetism. Numerical dynamo simulation has bloomed since the pioneering work of Glatzmaier and Roberts (1995) and has shown that, despite some deficiencies of the models, these can reproduce the main spatial and temporal properties of the geomagnetic field remarkably well (e.g., Christensen et al. 2010b). Much improvement has been made in the recovery of paleointensities (e.g., Tauxe and Yamazaki 2007). Comprehensive archeomagnetic (e.g., Korte et al. 2005; Genevey et al. 2008; Donadini et al. 2009) and paleomagnetic data sets (e.g., Biggin et al. 2009) have been built, and new field modelling strategies have been developed to make the best use of these data (e.g., Korte et al. 2009; Khokhlov et al. 2006). All these advances, among many others, are now providing new opportunities to bridge the gap between theory, numerical simulation, observations and, to some extent, also experiments.

It is in the context of this stimulating ongoing research, that ISSI offered us the opportunity to convene this Terrestrial Magnetism workshop. ISSI provides a generous venue. But it can only accommodate a finite number of participants. Selecting the scientific program and ensuring a balanced participation of the different active groups throughout the world was no easy task. More than forty participants (Fig. 1) finally attended, either giving talks or organising discussions, but in all cases actively participating in the workshop. These discussions led participants to identify topics they felt were most deserving of written contributions, and generate the series of reviews that the reader will find in the present volume. They provide both the latest perspectives on topics one would have expected to find in such a volume, and some considerations about emerging issues that are likely to guide future research.

Although the reader might be tempted to directly jump to specific reviews, we wish to stress that all papers are well worth reading in sequence, starting from the historical perspective given by Gubbins (2010). The first review to follow, by Matzka et al. (2010), gives an observer's account of the way magnetic data are acquired, with special emphasis on the modern global network of geomagnetic observatories. In a complementary way, Olsen et al. (2010b) next describe satellite concepts that have been used, will be used, or could be envisaged for measuring the Earth's magnetic field from space. The way these data can be processed to recover the lithospheric field (Thébault et al. 2010) and the time-varying core field (Gillet et al. 2010) are next discussed. Although many aspects of short-term core dynamics can now be observed, their interpretation is still lagging and remains the subject of much debate. Two reviews report on advances in this very active field of research, one focussing on the issues raised by the occurrence of sudden events known as geomagnetic jerks (Mandea et al. 2010), the other putting more emphasis on the way the magnetohydrodynamics of the Earth's core could be reconciled with these observations (Finlay et al. 2010). Turning to longer timescales, and to indirect data recovered from magnetized human artefacts and rock samples, Donadini et al. (2010) next report on the way these data can be converted into core field models in very much the same way as historical data, making it possible to extend our knowledge of the way the core field behaved over the past millennia. Such modern, historical and archeomagnetic core field models could also soon jointly be used to make even further progress in our understanding of the present state of the geodynamo, and allow us to envisage medium-term geomagnetic field predictions. Fournier et al.

Fig. 1 Participants in the Workshop on Terrestrial Magnetism, held at the International Space Science Institute, Bern, Switzerland, March 9–13, 2009. (1) Alexandre Fournier, (2) Dominique Jault, (3) André Balogh, (4) Cary Forest, (5) Vincent Lesur, (6) Jürgen Matzka, (7) John A. Tarduno, (8) Richard Holme, (9) Arnaud Chulliat, (10) Michael Purucker, (11) Kristof Petrovay, (12) Terence J. Sabaka, (13) Luis Silva, (14) Catherine L. Johnson, (15) Hagay Amit, (16) Erwan Thébault, (17) Nils Olsen, (18) Johannes Wicht, (19) Ulrich R. Christensen, (20) Julien Aubert, (21) Catherine G. Constable, (22) Mioara Mandea, (23) Karl-Heinz Glassmeier, (24) Elisabeth Canet, (25) Enkelejda Qamili, (26) Mathieu Dumberry, (27) Kathryn A. Whaler, (28) Roger-Maurice Bonnet, (29) Giuli Verbanac, (30) Philippe Cardin, (31) Alexandra Pais, (32) Monika Korte, (33) Fabio Donadini, (34) Benoit Langlais, (35) Andrew Tangborn, (36) Gauthier Hulot, (37) Nicolas Gillet, (38) Christopher C. Finlay, (39) Weijia Kuang, (40) David Gubbins, (41) Binod Sreenivasan

(2010) provide a general introduction to the emerging field of data assimilation in geomagnetism that could make this possible. For time scales of the core field only documented by paleomagnetic data, the next two reviews report on recent advances in paleomagnetic data acquisition and interpretation, and discuss comparisons between observations and numerical simulations. Amit et al. (2010) focus on polarity reversals, their characteristics and the conditions that favour their occurrence, while Aubert et al. (2010) discuss the time average field, dipole moment variations, the paleosecular variation, the geomagnetic polarity time scale and the long-term evolution of the core field, with some emphasis on the role of boundary conditions imposed by the mantle and the thermal evolution of the Earth. Finally, this series of reviews ends with two rather less conventional contributions. The first highlights what makes the solar dynamo so different from the geodynamo (Petrovay and Christensen 2010), and the second discusses the possible biological consequences of a geomagnetic reversal, possibly the question most often asked of any geo- or paleomagnetician! In this final review, Glassmeier and Vogt (2010) reassuringly conclude that no evidence of major biological consequences related to previous reversals has yet been found. This being said, it is important to recall that the current decrease of the Earth's magnetic field, particularly in the South Atlantic (Fig. 2), does have some consequence on technology in general and space technology in particular (e.g., Heirtzler 2002). Whether this decreasing trend could lead to a

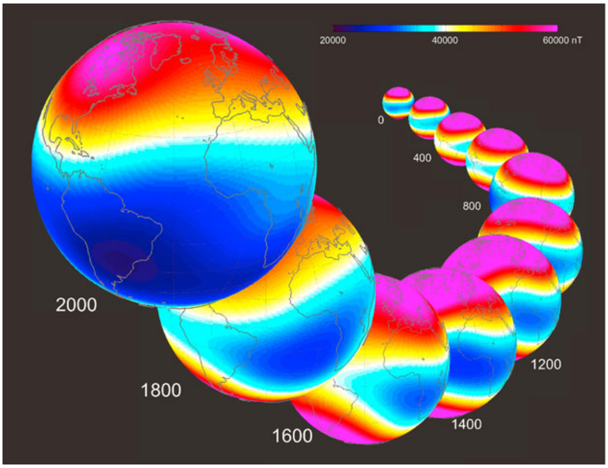

Fig. 2 Evolution of the intensity of the main magnetic field at the Earth's surface, between 0 AD and 2000 AD, as inferred from Korte et al. (2009), Jackson et al. (2000) and Olsen et al. (2010c). Note the global decrease of the Earth's intensity in the South Atlantic over the recent past

reversal is most likely unpredictable (Hulot et al. 2010b). But assessing whether it could last at least for the next few decades is a question that geomagnetic data assimilation, combined with permanent observation of the magnetic field, particularly from space, should soon be able to address.

Acknowledgements The Convenors of the Terrestrial Magnetism workshop are very grateful to ISSI, and particularly its Executive Director Roger-Maurice Bonnet, for the initiative of the workshop and support for its participants, and to Brigitte Schütte, Saliba Saliba and Katja Schüpbach for their very kind and efficient assistance. The Editors also wish to thank the participants who contributed to the present volume, and the reviewers who ensured that these contributions would meet the high standards required for publication in Space Science Reviews. This is IPGP contribution 3085.

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