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Geomagnetic Research from Space

The Decade of Geopotential Field Research, inaugurated in 1999 with the launch of the Danish satellite Ørsted on 23 February, was designed as an international effort to promote and coordinate continuous monitoring of geopotential field variability in the near-Earth environment. Since 1999, the Challenging Minisatellite Payload (CHAMP), the Gravity Recovery and Climate Experiment (GRACE), the Satélite de Aplicaciones Científicas-C (SAC-C), and most recently, the Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellites have combined with Ørsted to generate an unprecedented wealth of data on Earth's magnetic and gravity fields.

Interpretation of the new magnetic data from the Decade has led to improvements in scientists' knowledge of the fast changing small scales of the Earth's magnetic field, providing details of magnetic field generation within the Earth's core. The new magnetic data have also been used in the World Digital Magnetic Anomaly Map (WDMAM) project, which "images" the lithosphere's igneous and metamorphic rocks. Such data, associated theory, and modeling work also led to the discovery of previously undetected processes with magnetic signatures that can be observed by satellites, including oceanic tides, ionospheric pressure gradient currents and ionospheric plasma irregularities, and serpentinized mantle overlying subduction zones. Knowledge of the magnetic properties of these processes provides scientists with a new perspective of the physics involved in the phenomena.

CHAMP, one of the main data collectors for the Decade, may reenter the atmosphere by the end of 2009, depending on solar activity. CHAMP will be succeeded by Swarm, the fifth Earth Explorer mission in the European Space Agency's Living Planet Programme (Figure 1a). The new mission aims to measure the Earth's magnetic field with unprecedented accuracy through a constellation of three polar-orbiting satellites, designed to maximize the scientific return in the areas of core dynamics, lithospheric magnetization, and three-dimensional (3-D) mantle conductivity. It will also investigate electric currents flowing in the magnetosphere and ionosphere, quantify satellite drag in the upper atmosphere, and search for the magnetic signature of ocean circulation.

The Decade has given geomagnetic research endeavors a strong foundation. Swarm will build on these past accomplishments and usher in a new era in the study of geomagnetism through separating the multitude of sources contributing to the Earth's magnetic field.

By E. Friis-Christensen, H. Lühr, G. Hulot, R. Haagmans, and M. Purucker

Understanding the Effects of Internal Magnetic Fields

The sources of the Earth's magnetic field fall into two categories: The field is generated either from electric currents or from magnetized material. Electric currents can be found throughout the Earth system. The largest of these current systems is found inside the metallic core, but smaller current systems exist within the ionosphere, magnetosphere, and oceans. The current systems within the Earth's core are generated by a self-sustaining dynamo process and are closely tied to motions in the liquid metal outer core. Two main types of instruments are used to detect the geomagnetic field: fluxgate magnetometers, for measuring the direction of the field, and scalar magnetometers, for measuring its magnitude.

To learn more, scientists have recently looked to Mercury, the only other terrestrial planet besides the Earth with a planet-wide intrinsic magnetic field. Two recent flybys of the Sun's innermost planet by NASA's Mercury Surface, Space Environment, Geochemistry, and Ranging (MESSENGER) spacecraft have revealed that the large-scale morphology of Mercury's internal magnetic field [*Anderson et al.*, 2008] is similar to that of Earth's, although Mercury's surface field is 2 orders of magnitude weaker. Dominantly dipolar and spin-aligned, the fields of both planets possess significant nondipole moments, manifested as polar and equatorial magnetic "lows." In the case of Earth, the "low" is referred to as the South Atlantic anomaly, a region marked by a growing reverse flux patch on the top layer of the underlying core.

The South Atlantic anomaly is an oval-shaped geographic region in the southern Atlantic Ocean east of Brazil. Because of the relatively weak magnetic field here, particles from the Van Allen radiation belts have access to lower altitudes, and the associated increased radiation dose adversely affects satellites traveling through the region. This feature has existed since at least 1840 and is closely tied to the overall decrease of the strength of the Earth's dipole (5% per century) since that time [*Jackson and Finlay,* 2007]. Another large-scale phenomenon is the rapid motion of the north magnetic dip pole (where the field direction is vertical). Because the horizontal component of the magnetic field in the region of this pole exhibits a very flat gradient, small changes in the field can cause significant displacements of the pole [*Mandea and Dormy,* 2003].

What causes such changes in the field? Changes of internal origin can now be witnessed with unprecedented space and time

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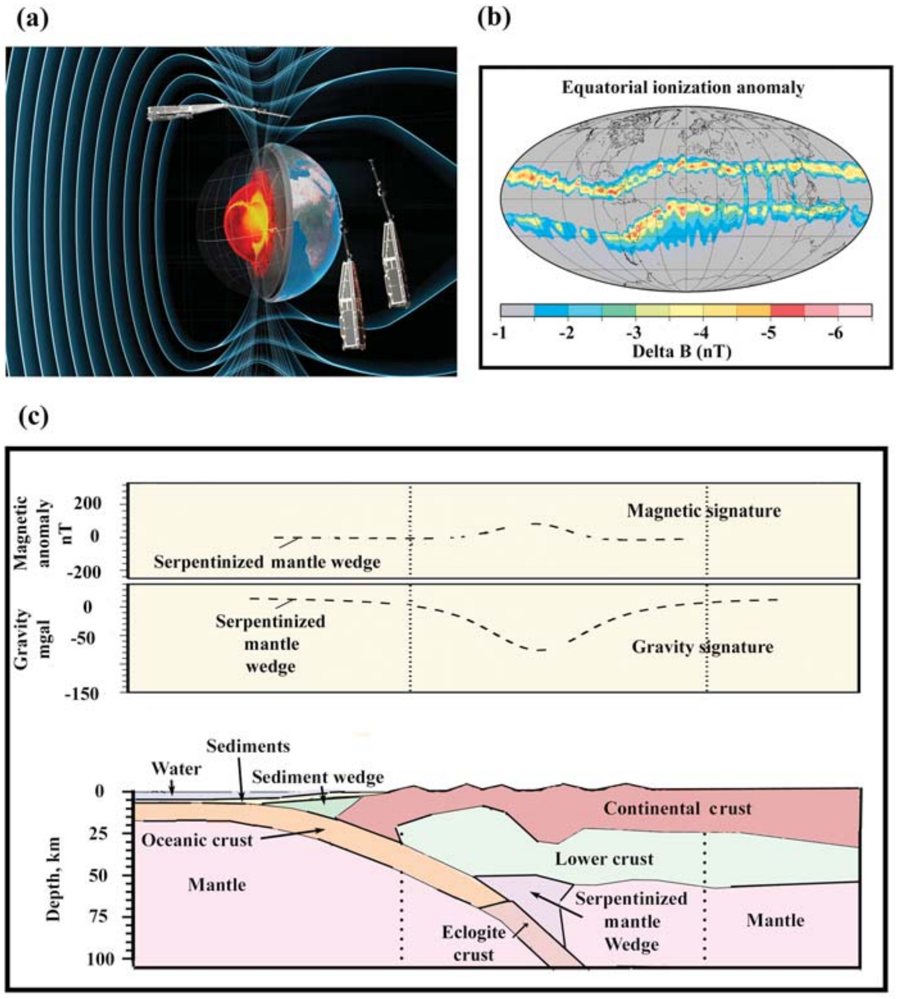

*Fig. 1. (a) Schematic of the upcoming Swarm constellation, set within the geomagnetic environment of the Earth. Image courtesy of the European Space Agency (ESA)/Advanced Operations and Engineering Services (AOES) Medialab. (b) Magnetic effect of the equatorial ionization anomaly after sunset at 400 kilometers in altitude, from 23 to 27 October 2001 [*Lühr et al.*, 2003]. The color bar represents the change in magnetic field* B*, measured in nanoteslas. (c) Crust and upper mantle model of subduction zone and related serpentinite mantle wedge associated with magnetic and gravity anomalies, the latter measured in milligals. Adapted from* Blakely et al. *[2005].*

resolution, providing detailed pictures of fast changing small-scale structures in the field produced within the core [*Hulot et al.*, 2002, 2007]. The dynamics of these features have been shown to affect the length-of-day variation and may testify to unexpectedly rapid flow changes in the Earth's core [*Olsen and Mandea*, 2008], a provocative suggestion that needs further validation from the Swarm mission.

Magnetic Anomalies

Although the magnetic fields from the Earth's core represent some 99% of the Earth's magnetic field, material in the Earth's crust and uppermost mantle produce fields that are easily measurable with sensitive magnetometers. This material is magnetized and is dominantly associated with igneous and metamorphic rocks rich in iron oxides, although sedimentary rocks also have subordinate but measurable magnetism. This magnetism is a function of temperature; rocks lose their magnetism as they approach their Curie temperature, typically 200°–700°C.

Studies of crustal magnetism have contributed to geodynamic models of the lithosphere, geologic mapping, and petroleum and mineral exploration. Maps of crustal magnetic fields, interpreted in conjunction with other information, have been used to locate diamond-bearing kimberlites and meteorite impacts. The depth of the magnetized rocks can be inferred by mapping the wavelength of the magnetic fields, with the deepest sources producing the longest wavelengths.

Through sensitive magnetometers on board satellites, airplanes, and ships, crustal magnetic fields have been mapped in the Magnetic Anomaly Map of the World, published in 2007 by the WDMAM project [*Korhonen et al.*, 2007]. The map represents the first global compilation of the wealth of magnetic anomaly information and was generated by combining CHAMP satellite data and aeromagnetic and seagoing surveys, supplemented by anomaly values estimated from a combination of oceanic crustal ages and a magnetic polarity timescale. Because information is collected from ground-based and satellite-based surveys, large-scale patterns and fine-scale fluctuations can be observed. A new generation of the map is planned for 2011 and will include many new data from oceangoing surveys, although the southern oceans still remain poorly surveyed.

The Earth's mantle is usually considered to be nonmagnetic because of mineralogy and elevated temperature, but investigations conducted during the Decade of Geopotential Field Research reveal that subduction margins may be an exception to this rule. Subducting oceanic slabs release water into overlying continental mantle, thereby transforming peridotite into serpentinite. Serpentinite often contains abundant magnetite, and thermal models suggest that cold, descending slabs cool the mantle to below the Curie temperature of magnetite, revealing its magnetic signature. Magnetic and gravity anomalies over subduction zones are commonly seen in satellite maps, and in the Cascadia and Alaskan subduction zones, for example, the depth of the sources of these long-wavelength anomalies has been estimated to lie within the mantle (Figure 1c, see *Blakely et al.,* [2005]).

Magnetic Signatures of Oceanic Tides

Newly recognized processes with satellite magnetic signatures also include the oceanic lunar semidiurnal (M_2) tide [*Tyler et al.,* 2003]. The semidiurnal tide possesses a magnetic signature because seawater is an electrically conducting fluid. The flow of this fluid through the Earth's main magnetic field in turn generates magnetic fields, but these do not affect the tidal flow to any significant degree.

The tidal signature was easily recognized because of a clear M_2 peak in the intensity spectra over the ocean data collected by CHAMP, in contrast to the land data where the peak was absent. Additionally, a global numerical prediction of these magnetic fields was in good agreement with observations. Of more importance for climate modeling, the magnetic signal associated with oceanic currents should be measurable by CHAMP, and soon by Swarm. However, the spatial scale of these signals overlaps with those from the core and crust, and they have not yet been isolated.

Complications to Measurements

Complicating satellites' ability to isolate the Earth's internal magnetic fields are a variety of magnetic fields from sources above the neutral atmosphere, in the region called geospace, several of which have been recognized for the first time as a consequence of high-resolution magnetometers and plasma instrumentation on CHAMP. Examples include the magnetic fields associated with regions of dense plasmas [*Lühr et al.*, 2003] or irregularities within the equatorial ionosphere [*Stolle et al.*, 2006], as well as with gravity-driven electric currents in the ionosphere [*Maus and Lühr,* 2006].

Electron density anomalies are prominent north and south of the magnetic equator, especially after sunset. These lead to magnetic field depletions of only one part in 10,000 (Figure 1b), which explains why they were not previously recognized. The magnitude and scale size of these features fall within the range of crustal anomalies, and earlier models of the crustal magnetic field often contained spurious signatures skewed by electron density anomalies. These features can also cause artifacts in main field models, especially in the secular variation and acceleration coefficients, due to the effect's dependence on the 11-year solar cycle.

Because the Swarm satellites will be at two different local times, external field effects and corresponding induced effects are more likely to be recognized and isolated. Extensive simulation studies have shown how satellites at multiple local times can be optimized to do the best job of separating internal, external, and induced fields.

Looking to the Future

New discoveries of processes through analysis of satellite magnetic signatures are expected to continue apace with Swarm. Swarm's constellation will include two spacecraft at low altitude, measuring the east-west gradient of the magnetic field, and one at higher altitude in a different orbital plane. The new satellites will carry instrumentation to measure the vector and scalar magnetic fields, electric fields and plasma parameters, nongravitational accelerations, and position (with the Global Positioning System). In addition, by making it possible to access the detailed evolution of the field at the top layer of the underlying core over a significant time period, data assimilation procedures may be used to predict the future behavior of the Earth's magnetic field.

Work on prediction already has begun, with promising results [*Fournier et al.,* 2007; *Liu et al.,* 2007]. The improved local time coverage of the Swarm satellites will significantly advance studies of the 3-D electrical conductivity of the mantle. Conductivity variations often correspond to large-scale variations in water content, and this approach could complement seismic techniques for imaging subducted slabs within the mantle. Finally, the magnetic signature of subduction and serpentinization will allow for detailed study of the possible connection between intraslab earthquakes and the hydrated fore-arc mantle [*Blakely et al.,* 2005].

Expected results from Swarm and new results from CHAMP and Ørsted will be presented at the Second Swarm International Science Meeting, held at the German Research Centre for Geosciences (Deutsches GeoForschungsZentrum (GFZ)), in Potsdam, Germany, from 24 to 26 June 2009. For more information on geomagnetic research, and its applications, please visit http://www.esa.int/esaLP/LPswarm.html.

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