GEOPHYSICAL RESEARCH LETTERS, VOL. 30, NO. 17, 1906, doi:10.1029/2003GL017407, 2003

The diamagnetic effect of the equatorial Appleton anomaly: Its characteristics and impact on geomagnetic field modeling

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Received 26 March 2003; revised 28 May 2003; accepted 14 July 2003; published 12 September 2003.

[1] The diamagnetic effect generally reduces the magnetic field inside a plasma. Its importance is appreciated in regions like the magnetosphere and the solar wind. In the ionosphere, depletions of the geomagnetic field have up to now been considered negligible. The CHAMP satellite provides for the first time the combination of high-resolution magnetic field measurements and plasma density observations on the same spacecraft in low-Earth orbit. We show the typical distribution of electron density at the altitude of about 430 km for various local times. Particularly prominent features are the density enhancements north and south of the dip equator. As expected, the magnetic field intensity is depressed in the crest region by an amount of more than 5 nT. The diamagnetic effect is strongest from sunset to midnight and thus causes errors in global geomagnetic field models which are usually computed from data sampled at all night-time hours. *INDEX TERMS:* 2467 Ionosphere: Plasma temperature and density; 2415 Ionosphere: Equatorial ionosphere; 2409 Ionosphere: Current systems (2708); 1517 Geomagnetism and Paleomagnetism: Magnetic anomaly modeling. **Citation:** Lühr, H., M. Rother, S. Maus, W. Mai, and D. Cooke, The diamagnetic effect of the equatorial Appleton anomaly: Its characteristics and impact on geomagnetic field modeling, *Geophys. Res. Lett.*, *30*(17), 1906, doi:10.1029/2003GL017407, 2003.

1. Introduction

[2] Charged particles in a magnetized plasma orbit around the lines of force in such a way that the generated magnetic moment is oriented oppositely to the ambient magnetic field. The strength of the magnetic moment depends only on the particle's temperature divided by the ambient field magnitude. The resulting field depletion is called the diamagnetic effect of plasma. This effect has been convincingly demonstrated in space, for example, by the ion release experiments of the AMPTE-IRM satellite. Within the dense cloud of released chemicals the magnetic field initially vanished completely and came back when the density was sufficiently depleted [e.g., *Lühr et al.*, 1986a, 1986b].

[3] As an alternative to this microscopic picture one can give a macroscopic description of the diamagnetic effect. This involves currents flowing perpendicular to the pressure gradient and the ambient magnetic field. The direction of the currents is again such that they reduce the magnetic field strength in the high-pressure region. In case of a constant temperature the pressure is controlled by the electron density. Whenever plasma pressure gradients built up, such compensating currents are induced. The intensity of these currents is independent of the ionospheric conductivity.

[4] There is a third way of describing the diamagnetic effect. In a quasi-stationary case (provided the pressure gradients are not too steep, so that magnetic tension can be neglected), the sum of magnetic and plasma pressure tends to be constant. When the plasma pressure, (scaling with number density and temperature), is enhanced, the magnetic pressure, (and, hence, the ambient field strength), must be reduced.

[5] The Appleton or equatorial anomaly denotes regions of enhanced plasma density some 10° to 15° in latitude north and south of the dip equator, occurring from pre-noon through midnight hours. The underlying effect is an uplift of ionospheric plasma to altitudes where the recombination rate is significantly reduced. The daytime dynamo-generated eastward electric field causes an uplift of ionospheric plasma at the dip equator. This carries plasma parcels to altitudes of 700 km and more. After losing momentum, the electrons and ions diffuse along the magnetic field lines to either side of the equator to form the anomaly. The largest anomaly is observed during the hours following sunset. This general picture is supported both by simulation studies [e.g., *Hanson and Moffett*, 1966; *Bailey et al.*, 1997] and observational data, as reviewed by *Raghava Rao et al.* [1988]. The temporal and spatial development of the equatorial anomaly along a meridian profile at 121°E has been studied in detail by *Yeh et al.* [2001].

[6] For high-resolution magnetic field measurements the readings may locally be affected by the plasma density. This effect has never been accounted for in any of the previous magnetic field missions. CHAMP is the first satellite carrying a suite of high-resolution magnetic field instruments, together with a Langmuir probe to determin the local electron density. In this letter we address the questions, to what extend the equatorial anomaly affects magnetic field modeling efforts and ionospheric current estimates, and how it can be corrected.

2. Observations

[7] The CHAMP satellite was launched on July 15, 2000 into a circular, near-polar (incl. = 87.3°) orbit with an initial altitude of about 450 km which has decayed to some 400 km after two years. One of the mission objectives is the study of the geomagnetic field. Instruments supporting these investigations are an absolute scalar magnetometer, a vector fluxgate magnetometer, a dual-head star camera system, and a digital ion driftmeter, including a Planar Langmuir Probe (PLP). Further details of the CHAMP

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0094-8276/03/2003GL017407$05.00

satellite and mission can be found at the web site http://op.gfz-potsdam.de/champ/.

[8] In this study we are primarily interested in the diamagnetic effect. It is thus justified to consider only the magnetic field magnitude, as measured by the scalar Overhauser magnetometer, and the electron density, as derived from the PLP readings. Since we are particularly interested in the effect on magnetic field modeling efforts, we have limited our attention to magnetically quiet periods with Kp < 2+.

[9] At first, we give an impression of the temporal and spatial behavior of the Appleton anomaly at CHAMP orbital altitudes (430 km). Figure 1 shows the diurnal variation of electron density structures at low latitude. For one longitude (90° ± 5°E) individual latitude profiles are displayed for each uneven hour in local time, as a stacked plot.

[10] The orbit of CHAMP precesses through local time (LT) at a rate of 1 hour per 11 days. To cover all local times, a period of about four months is required. The measurements shown in Figure 1 were taken from the period ranging from 18 July to 5 November 2001. It has been chosen to be centered approximately about the fall equinox.

[11] The individual curves show a certain day-to-day and seasonal variability, but typical diurnal features can clearly be discerned. During the hours after midnight and before sun rise (01, 03, 05 LT) low densities are observed. As expected, the electron concentration rises in the morning hours. At 11 LT the Appleton anomaly is already formed. During the afternoon hours the density remains high. After sunset the equatorial ionosphere becomes more dynamic and the Appleton anomaly remains prominent until midnight.

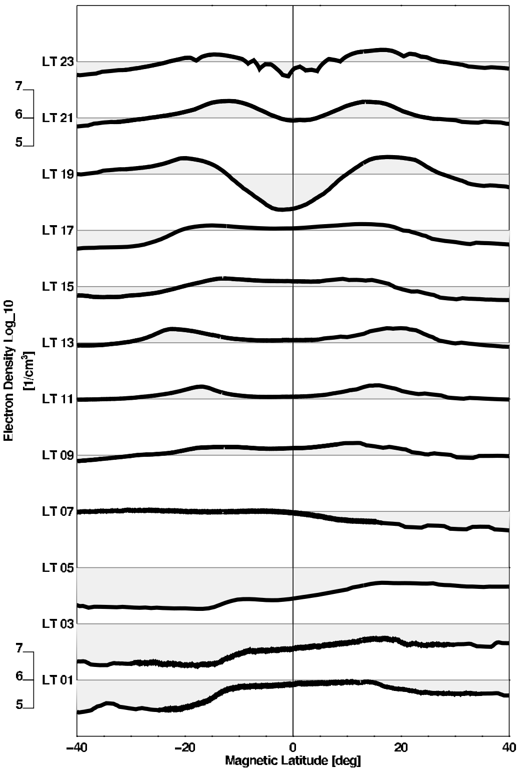

Figure 1. Profiles of the electron density for different local times (LT), sampled along the 90°E longitude at an altitude of about 430 km. Density variation relative to a baseline of $1 \cdot 10^{-6}$ cm^{-3} has been emphasized by shading.

[12] After having seen the typical diurnal variation for a single longitude it is interesting to see the global distribution of electron density for a fixed local time. Figure 2 shows the electron density anomaly at all longitudes for the 20 LT sector averaged over 5 days. This is the local time when it is most pronounced. Evidently, the anomaly tracks the dip equator and peaks some 15° north and south of it. For certain longitudes the valley between the peaks is so deep that the instrument runs out of signal. This is often called the evacuation of the equatorial ionosphere.

[13] Our prime interest is the effect of enhanced plasma density regions on the magnetic field measurements. Since the diamagnetic effect is expected to be small compared to the contributions from other magnetic field sources, all of the other parts have to be removed accurately before the signature of interest can be detected reliably. The main field was removed from the scalar data by subtracting a recent field model (Ørsted-05m-02 *Olsen*, 2002]). In addition the lithospheric magnetization was eliminated by subtracting an appropriate crustal field model [*Maus et al.*, 2002].

[14] Figure 3 shows, as examples, residual magnetic field variations together with electron density measurements for three different local times. It is immediately evident that density peaks are accompanied by depletions in field strength.

[15] The solid lines in Figure 3 represent the magnetic field measurements, while the dashed lines are proposed corrections, as described below. The top frame contains an example from early morning (04 LT). At that time the electron density is low and little effect is expected. In the middle panel we show the situation around noon. The magnetic field signature is dominated by the effect of the equatorial electrojet (EEJ) (minimum at dip equator). The density profile exhibits two clear maxima. Collocated with the density peaks we find local minima in the magnetic field trace. The field correction partly fills these minima. The bottom frame presents an example from 20 LT. This is the time when high densities are encountered at the Appleton anomaly. The residual magnetic field strength again exhibits depressions at the latitudes of the density peaks. In this case the corrected magnetic field differs significantly from the observed one.

3. Discussion

[16] We have presented observational evidence that the diamagnetic effect can cause significant field strength depletions visible in the CHAMP magnetic field measurements. Let us now treat the effect more quantitatively. As mentioned above, from the macroscopic point of view the field reduction is caused by currents flowing at the pressure gradient. The current density, **j**, driven by a pressure gradient, can be written as:

$$\mathbf{j} = -k/B^2\{\nabla[n(T_i + T_e)]\} \times \mathbf{B}, \qquad (1)$$

where k is the Boltzmann constant, T_e and T_i are the electron and ion temperatures, n the electron density and **B** the

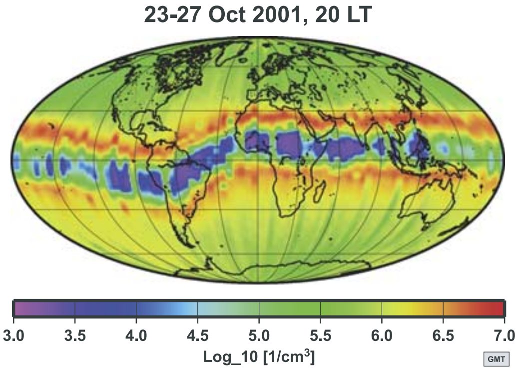

Figure 2. Longitude variation of electron density in the 20 local time sector.

magnetic field vector with its magnitude B. When computing the magnetic effect of these currents the geometry of the pressure gradient has to be known. This requires the knowledge of the density and temperature distribution, including their gradients, within of the whole region including their gradients. From our measurements we have, however, only the electron density along the orbit track. For the ion and electron temperature we rely on model estimates [*Köhnlein*, 1986]. This model predicts a moderate variation of the ion temperature during quiet times. For the electrons clearly higher temperatures are expected at the poles than at the equator. Also the difference between day and night is substantial. If we are interested in a fixed local time and a limited latitudinal range, the sum of ion and electron temperature can be regarded as constant.

[17] In this study we follow the third approach given in the introduction. Based on the assumption of a stationary momentum equation every increase in plasma pressure has to be counter-balanced by a reduction in the magnetic pressure.

$$\frac{(B-b)^2}{2\mu_0} + nk(T_i + T_e) = \text{const.}, \tag{2}$$

where μ_0 is the susceptibility of free space, b is the diamagnetic effect and n the number density. It is reasonable to assume a single ion species (O^+) at CHAMP altitudes. Therefore T_i is the temperature of oxygen ions, which ranges around 1000 K. The electron temperature is close to the ion temperature throughout the night, but rises above 2000 K at noon. Since the magnetic pressure is at least three orders of magnitude higher than the plasma pressure in the ionosphere, we may apply a linear perturbation approach:

$$\frac{bB}{\mu_0} = nk(T_i + T_e) \tag{3}$$

and subsequently

$$b = nk(T_i + T_e)\frac{\mu_0}{B}. \tag{4}$$

[18] Inserting typical values in equation (4), as determined by our measurements for the late evening, $n = 4 \cdot 10^{12}$ m^{-3}, $(T_i + T_e) = 2000$ K, $B = 30000$ nT, we obtain a diamagnetic effect of $b = 5$ nT. The example for 20 LT, presented in Figure 3, shows magnetic field depletions of the order of 5 nT which is consistent with the predicted effect.

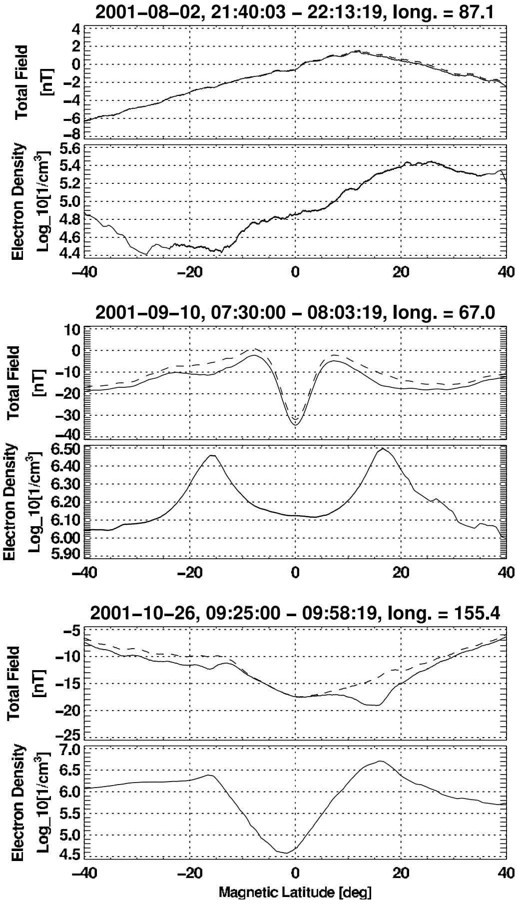

Figure 3. Concurrent magnetic field and electron density measurements for three different local times, top: 04 LT, middle: 12 LT, bottom: 20 LT. Full lines in the magnetic field frames show observations, broken lines reflect readings corrected for the diamagnetic effect.

[19] Conversely, equation (4) can be used to correct for the diamagnetic effect. The only quantities for which we have to make assumptions are the ion and electron temperatures. From the model of *Köhnlein* [1986] we read for the

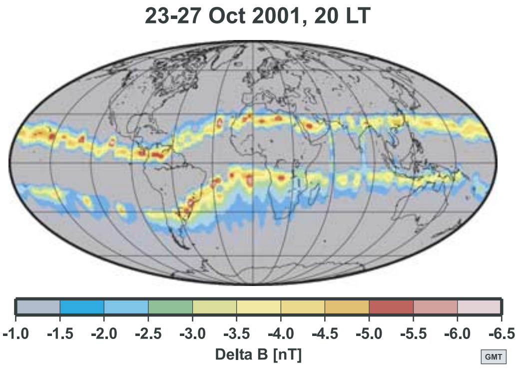

Figure 4. Global distribution of the depletion in total field caused by the diamagnetic effect in the 20 local time sector (same period as for Figure 2).

times of measurements and altitude of CHAMP the following temperatures, ions at night-time 900 K, at noon 1100 K. For the electrons we also get 900 K at night, and 2400 K around noon. For n we take the observed electron density.

[20] The dashed lines in Figure 3 are corrected magnetic fields according to equation (4). In case of the noon-time example the local minima at the wings of the EEJ signature are partly removed by the field correction. Although being small in amplitude this change in shape has a significant consequence for EEJ current estimates, in particular for the role of return currents. These return currents are significantly over-estimated in case no correction is applied. The largest diamagnetic effects are encountered during post-sunset hours. The corrections in the bottom frame of Figure 3 amount to some 6 nT, which is twice the strength of the mean crustal field [e.g., *Maus et al.*, 2002]. After applying the correction the magnetic field curve is much more symmetrical about the magnetic equator, as expected for the ionospheric currents in the late evening.

[21] Data from the late evening and pre-midnight hours have generally been included in magnetic field models [e.g., *Olsen*, 2002]. In order to give an impression of the size and global distribution, Figure 4 shows the deficit in magnetic field strength, as computed from equation (4), for the five-day average presented in Figure 2.

[22] In this letter we considered the diamagnetic effect only with respect to the field magnitude. An inspection of the perpendicular magnetic field components (not shown here) reveals that there are no local modifications observable, as long as the Appleton anomaly has a smooth shape (Figures 1 and 3). Quite frequently, however, the build-up of plasma instabilities and the formation of equatorial plasma bubbles can be observed during the post-sunset hours. In such cases of steep gradients the perpendicular field components are also affected. The magnetic signatures associated with those phenomena have been briefly addressed by *Lühr et al.* [2002] and will be the subject of a more extended study. Although this study focuses on the Appleton anomaly, a regional phenomenon of plasma density enhancement, any plasma pressure variation generates a diamagnetic effect, and corrections should be considered wherever applicable. This is particularly true when satellite measurements are mapped to the ground. For the mitigation of this problem in field modeling studies one could limit the data selection to hours with low ambient plasma density, e.g. after midnight and before sunrise, as is evident from Figure 1. *Maus et al.* [2002] have taken this into account when modeling the lithospheric magnetization.

[23] Nowadays, multi-satellite missions are being planned in order to improve the accuracy and resolution of magnetic field models. In such cases the diamagnetic effect requires particular attention, and adequate instrumentation for proper plasma diagnostic should be foreseen. A constellation of several spacecraft cruising at different altitudes and local times will help to distinguish between the various field sources, but an uncorrected local effect in the 5 nT range can easily lead to a significant misinterpretation of the field contributions.

4. Conclusion

[24] We have shown that the magnetic field strength is diminished by around 5 nT within the plasma enhancements of the Appleton anomaly. This value is close to the prediction derived for the diamagnetic effect. CHAMP is the first satellite mission combining high-resolution measurements of geomagnetic field and ionospheric plasma parameters. This allows for both outlining the consequences of neglecting this effect, but also to correct for it. For example, satellite studies of the equatorial electrojet are severely affected by the diamagnetic effect. If not considered this lead to significant discrepancies between ionospheric current distributions estimated from ground and space. The latitudinal scale-size of the Appleton anomaly falls into the range of crustal anomalies. For that reason this spurious effect may show up in lithospheric field models. Due to the systematic depletion of the magnetic field strength and due to the global extent in longitude the diamagnetic effect will also cause artifacts in main field models, particularly in high-degree secular variation and acceleration coefficients.

[25] For all of these reasons future satellite missions, intended to monitor and study the geomagnetic field, should be equipped with diagnostic tools for measuring the plasma density and temperatures. This is particularly important, if dedicated constellation missions are considered, such as the proposed ESA mission *swarm*.

[26] **Acknowledgments.** We would like to thank M. Förster for fruitful discussions. The operational support of the CHAMP mission by the German Aerospace Center (DLR) and the financial support for the data processing by the Federal Ministry of Education and Research (BMBF) are gratefully acknowledged. This study was performed as part of the DFG Priority Program "Geomagnetic Variation", SPP1097.

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