DIPOLE MOMENT VARIATION

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The present geomagnetic field is approximately that expected from a dipole located at the center of the earth and tilted by about 11° relative to the rotation axis. The magnetic moment associated with such a dipole can be inferred from measurements of magnetic field strength. Systematic measurements of relative field strength revealing latitudinal variations were made by De Rossel on the D'Entrecasteaux expedition (1791-1794), but the moment was not evaluated directly until the 1830's when **Gauss** (q.v.) carried out the first spherical harmonic analysis using absolute measurements of field strength made at geomagnetic observatories. Although the dipole moment has decreased by about 10% since then, the current value of 7.78×10^{22} Am^2 is close to the average for the past 7 kyr (7.4×10^{22} Am^2). A broad range of geomagnetic and paleomagnetic observations indicates that both these values are higher than the longer term average, but probably not anomalously high, and that the current rate of change seems not atypical for Earth's history. Changes in the dipole moment occur on a wide spectrum of time scales: in general, changes at short periods are small, and the greatest variations are those associated with excursions and full reversals of the geomagnetic field.

1. Dipole Moments and their Proxies

How the dipole moment is estimated depends on the information available. The geomagnetic dipole moment m can be computed directly from the degree 1 Gauss coefficients, g_1^0, g_1^1, and h_1^1, of a **spherical harmonic** (q.v.) field model via

$$m = \frac{4\pi a^3}{\mu_0}\sqrt{(g_1^0)^2 + (g_1^1)^2 + (h_1^1)^2},$$

with a the average radius of the Earth, and μ_0 the permeability of free space. This clearly distinguishes the dipole from **non-dipole field** (q.v.) contributions. When there are insufficient data to construct a field model, p can be calculated as a proxy for m using a single measurement of magnetic field strength B,

$$p = \frac{4\pi a^3}{\mu_0}\frac{B}{\sqrt{1 + 3\cos^2\theta}}.$$

When θ is the geographic colatitude at which B is measured, p is known as a virtual axial dipole moment (VADM). This is the equivalent moment of a magnetic dipole aligned with the rotation axis that would generate the observed value of B. Often the magnetic inclination I is used to derive the magnetic colatitude θ_m via the relationship

$$\tan I = 2\cot\theta_m$$

When θ_m is used in place of θ, the result is known as a virtual dipole moment (VDM). In principle the VDM might take account of the tilt of the dipole axis, but the effect is complicated by the contribution of the non-dipole field present in any instantaneous measurement. VADM and VDM are most often used in comparing paleomagnetic data to account for gross geographic variations in field strength. Temporal and spatial averages of p are sometimes referred to as paleomagnetic dipole moments (PDMs); the hope is that such averages will remove the influence of non-dipole field contributions, but recent work indicates the possibility of substantial bias. Paleomagnetic measurements of field strength can be absolute or relative variations with time. Absolute measurements require a thermal origin for the magnetic remanence, while the relative variations commonly acquired from sediments must be tied to an absolute scale. A review of current paleointensity techniques can be found in Valet (2003).

Cosmogenic radioisotopes such as ^{14}C, ^{10}Be and ^{36}Cl are produced in the stratosphere at a rate that is expected to follow a relationship approximately inversely proportional to the square root of Earth's dipole moment (Elsasser *et al.*, 1956). Thus cosmogenic isotope records can serve as a proxy for relative dipole moment changes. Production rates are also affected by solar activity, but such changes seem largest on time scales short compared with the dipole moment variations. For ^{14}C the effects of exchange of CO_2 between atmosphere and ocean must be considered, resulting in substantial smoothing and delay in the recorded signal.

2. Direct Estimates for the Period 0-7 ka

Today the most complete mapping of the magnetic field is achieved using magnetometers on board satellites (*e.g.*, **Oersted** (q.v.)and **CHAMP** (q.v.)) that orbit Earth at an altitude of several hundred kilometers. These data are sufficiently dense and accurate that when combined with observatory measurements it is possible to obtain spherical harmonic models and detect changes in Earth's dipole moment of the order of 10^{18} Am^2 on time scales as short as a day. Such short term variations (and at least some of the changes up to periods as long as or longer than the solar cycle) do not reflect changes in the internal part of the magnetic field, but stem from fluctuations in strength of the solar wind. The solar wind modulates the strength of the external ring current that exists between about 3 and 6 earth radii and is the source of induced magnetic field variations in Earth's moderately electrically conducting mantle. Short term variations in dipole moment presumably also arise in Earth's core, but will be attenuated by passage through the electrically conducting mantle. On time scales of months to several tens of years it remains a challenge to separate variations of internal and external origin.

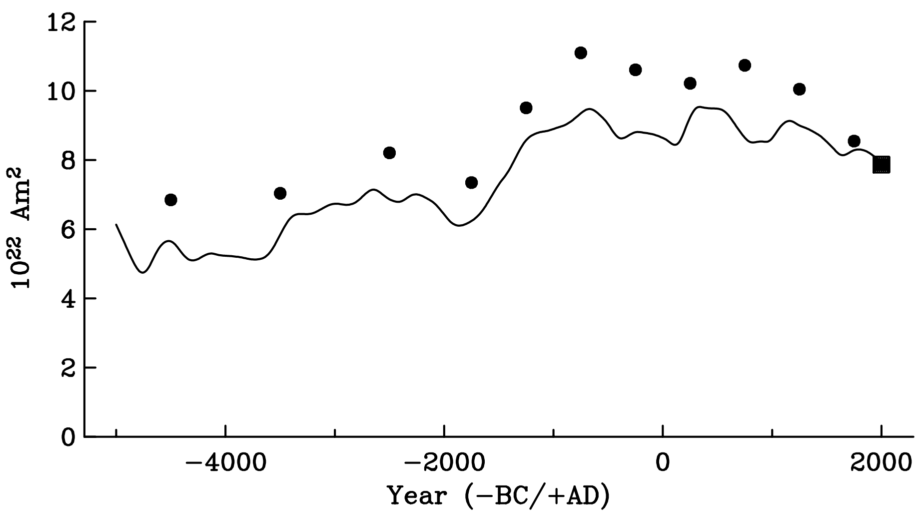

Figure 1: Comparison of estimated dipole moment m (continuous curve) with VADM proxies, p, (circles) for the past 7kyr, each based on the same archeomagnetic intensity data. Square gives the dipole moment from spherical harmonic analysis in 2002.

For longer term changes in dipole moment we turn to models constructed from the historical and paleomagnetic record. An excellent **time dependent model of the main magnetic field** (q.v.) is available for 1590-1990 AD (Jackson *et al.*, 2000) but is artificially scaled prior to 1832. Early attempts to extend knowledge of the dipole moment back in time used proxy VDMs and VADMs from archeomagnetic artefacts and lava flows for the past 50 kyr (McElhinny and Senanayake,1982) and indicated that 2000 years ago the dipole moment was almost 50% higher than today. Time-varying spherical harmonic models now exist for the past 7 kyr, and these allow separation of dipole and non-dipole variations. Directional data used in these models come from archeomagnetic artefacts, lava flows, and high deposition rate sediments. For intensity, only absolute measurements from archeomagnetic samples and lava flows were included. The resolution depends on the accuracy of the dating and the quality of the observations which is lower than for direct measurements, and also more heterogeneous, but the dipole moment agrees well with that inferred from historical data in the overlapping time range. Figure 1 shows the dipole moment for the period 0-7 ka, along with VADM calculated for the same data. The estimated dipole moment m is systematically lower than the

VADM, but still shows almost a factor of two in variability. The differences are consistent with geographical and temporal bias in sampling of the non-dipole field by the available VADMs (Korte and Constable, 2005).

3. Proxy Records from Sediments for 10 kyr - 1 Myr time scales

On longer time-scales the view of dipole moment variation is far less complete, although the situation is steadily improving. There are no direct estimates of m so we must rely on VADMs or some other proxy. Relative paleointensity variations in sediments are available from a large number of marine sediment cores (again see Valet, 2003) at a variety of locations and a range of time intervals. Global stacks and averaging of these records have been used as a proxy for dipole moment variation, initially for the time interval 0-200 ka and more recently for 0-800 ka (the SINT800 record). Longer stacked records will undoubtedly be forthcoming. Detailed analyses of the stacking process have been conducted with simulations of probable noise processes applied to output from numerical dynamo simulations. These show that although individual sedimentary records may be of low quality and inconsistent with others from nearby sites such techniques can recover long term variations in dipole moment. The resolution of changes in the record is primarily limited by the quality of the age control and correlations among cores, which depends on sedimentation rate and other environmental factors, but for SINT800 is probably around 20 kyr. Regional stacks for the North and South Atlantic regions have better temporal resolution because of higher average sedimentation rates. Some researchers hope to use dipole moment or regional paleointensity variations as a stratigraphic correlation tool, but large local variations in the non-dipole field may prevent this from being a useful approach.

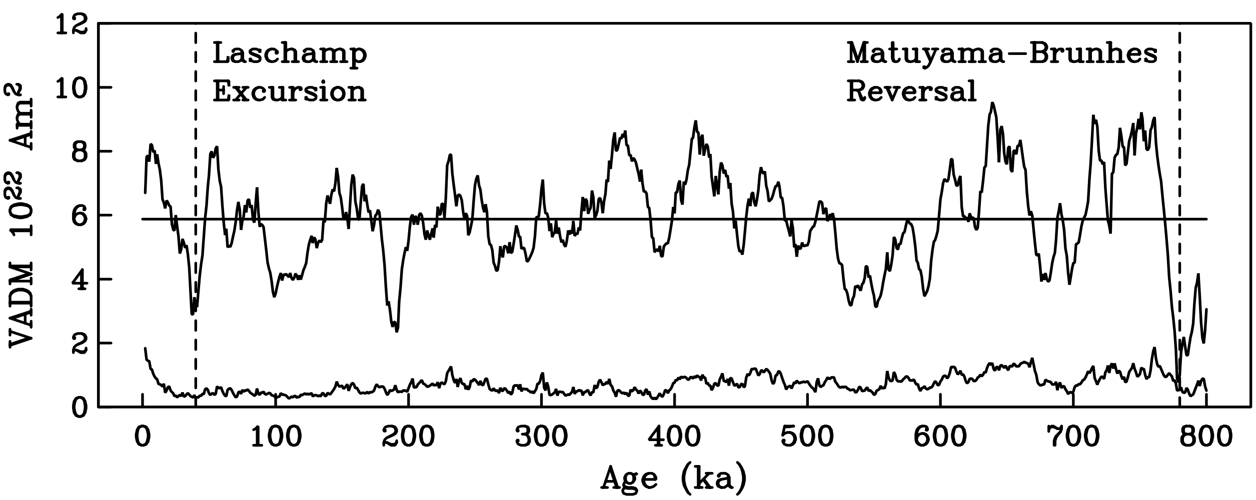

Figure 2: Variations in virtual axial dipole moment inferred from globally distributed marine sediments. upper curve gives average VADM, lower curve is one standard error in the mean. More details are given in Valet (2003).

The absolute calibration of relative variations in global dipole moment remains difficult, but the general pattern is well understood for the past few Myr at a resolution of a few tens of kyr. For the past 800 kyr a mean value of 5.9×10^{22} Am^2 is estimated for the global dipole moment, about 25% lower than its current value. SINT800 shows unequivocally (Figure 2) that there are repeated large but irregular changes in VADM over the past 800 kyr: the standard deviation is a little more than 25% of the mean for the entire record (almost certainly an underestimate of the true field variability because of heavy averaging). Excursional geomagnetic field behavior in field direction (most recently the Laschamp excursion at about 40 ka), are concurrent with low values of VADM, although the converse is not necessarily true, and the lowest value corresponds to the Matuyama-Brunhes geomagnetic reversal. The exact number of excursions catalogued during the Brunhes normal chron ranges from about 6 to 12 depending on the extent to which one requires global correlations among records. Paleointensity records from volcanics almost exclusively support the notion that excursions are associated with large decreases in geomagnetic intensity, and the idea that geomagnetic reversals are accompanied by a decrease of 80 or 90 % in dipole moment is essentially undisputed. Independent support for sedimentary relative paleointensity variations is provided by the general agreement with proxy dipole moment variations derived from the cosmogenic isotopes ^{10}Be and ^{36}Cl.

4. Proxy Records from TRMs and Longer Time Scale Variations

In principle, absolute paleointensity measurements on bulk samples and single crystals derived from lava flows and submarine basaltic glass provide the highest quality measurements of the geomagnetic field. The picture that emerges for VADM variations is slowly clarifying as the number of results steadily increases, and it becomes possible to evaluate the quality of the available data through the implementation of consistency checks on laboratory work, and replicate data on specimens from the same sample. Over the time interval 0-160 Ma the average dipole moment is estimated as 4.5×10^{22} Am^2 with a standard deviation of 1.8×10^{22} Am^2. The data are reasonably approximated by a log-normal distribution (Tauxe, 2005).

It remains hard to make definitive statements about very long term changes in dipole moment, because of the large geographic (1 standard deviation is about 18% for the present field) and temporal variability in p. The relationship between average intensity and reversal rate is still unclear, although at 8.1×10^{22} Am^2 the average VADM for the Cretaceous Normal Superchron is high and also highly variable(1 standard deviation = 4.3×10^{22} Am^2, Tauxe & Staudigel, 2004)). Other times during the Cenozoic show a weak correlation between average field strength and polarity interval length, although for short intervals this may reflect a significant contribution to the average from the low dipole strength during reversals. Higher average intensities are also correlated with greater variability in VADM, indicating that dipole and non-dipole variations may be covariant. It is clear that the average dipole moment depends on the time interval used for the calculation.

Some researchers have inferred correlations between changes in Earth's orbital parameters and geomagnetic field variations. There is to date no undisputed demonstration of such a relationship. Another outstanding question concerns the very ancient geomagnetic field. The field is known to have existed at 3.5 Ga and reversals have been documented from as early as 1.5 Ga (Dunlop and Yu, 2004), but there are so few data that it is not known whether the early field was really dipolar. Many more data are needed to test exciting hypotheses such as whether the nature of geomagnetic field variations changed with the formation and growth of the inner core.

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Cross References geomagnetic temporal spectrum; non-dipole field; excursions; reversals; cosmogenic radioisotopes; spherical harmonic; Gauss; Oersted; Champ; time dependent model of the main magnetic field