

**GEOMAGNETIC TEMPORAL SPECTRUM**

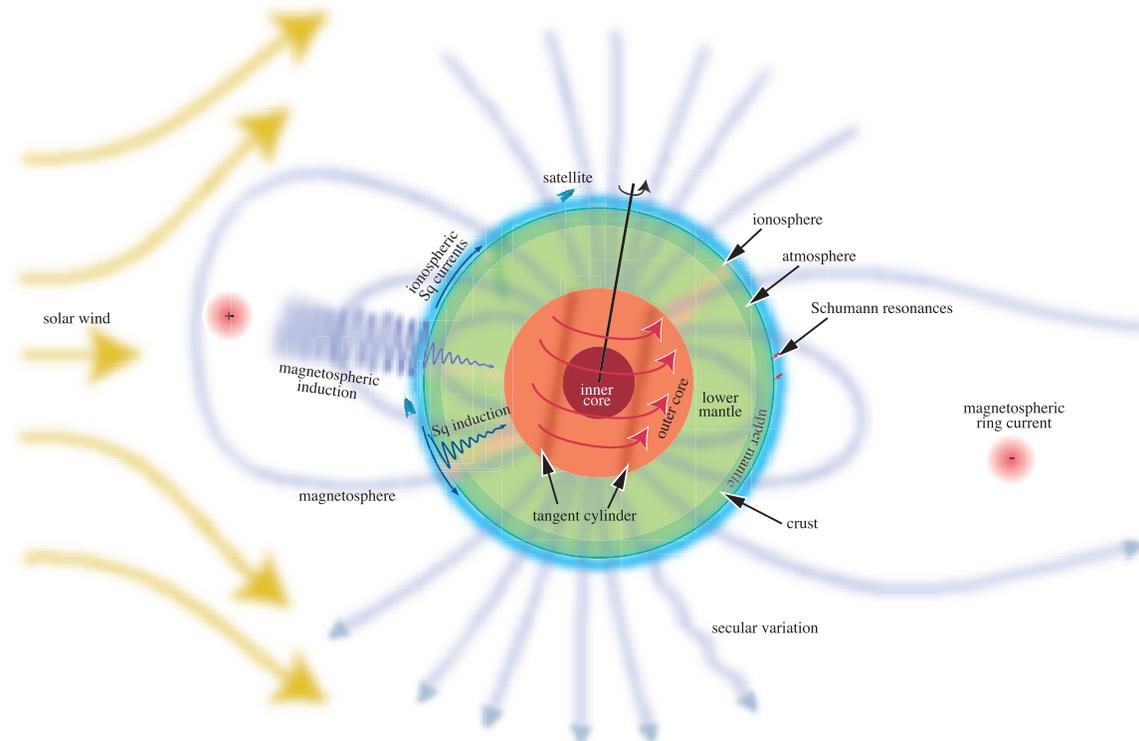
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## GEOMAGNETIC TEMPORAL SPECTRUM

The geomagnetic field varies on a huge range of time scales, and one way to study these variations is by analyzing how changes in the geomagnetic field are distributed as a function of frequency. This can be done by estimating the spectrum of geomagnetic variations. The power spectral density  $S(f)$  is a measure of the power in geomagnetic field variations at frequency  $f$ . When integrated over all frequencies it measures the total variance in the geomagnetic field.



**Figure 1:** Schematic illustration of the physical processes that contribute to the geomagnetic field, from Plate 1 of Constable and Constable, (2004), Copyright American Geophysical Union and reproduced with their and authors' permission.

Figure 1 shows a schematic of the various processes that contribute to the geomagnetic field, and these can be roughly divided according to the frequency range in which they operate. The bulk of Earth's magnetic field is generated in the liquid **outer core**, where fluid flow is influenced by Earth rotation and the geometry of the **inner core** (q.v.). **Core flow** (q.v.) produces a secular variation in the magnetic field, which propagates upward through the relatively electrically insulating **mantle** and **crust**. Short term changes in core field are attenuated by their passage through the mantle so that at periods less than a few months most of the changes are of external origin. The crust makes a small static contribution to the overall field, which only changes detectably on geological time-scales making an insignificant contribution to the long period spectrum. Above the insulating atmosphere the electrically conductive **ionosphere** (q.v.) supports **Sq** (q.v.) currents with a diurnal variation as a result of dayside solar heating. Lightning generates high frequency **Schumann resonances** in the Earth/ionosphere cavity. Outside the solid Earth the **magnetosphere** (q.v.), the manifestation of the core dynamo, is deformed and modulated by the solar wind, compressed on the sunside and elongated on the nightside. At a distance of about 3 earth radii, the magnetospheric ring current

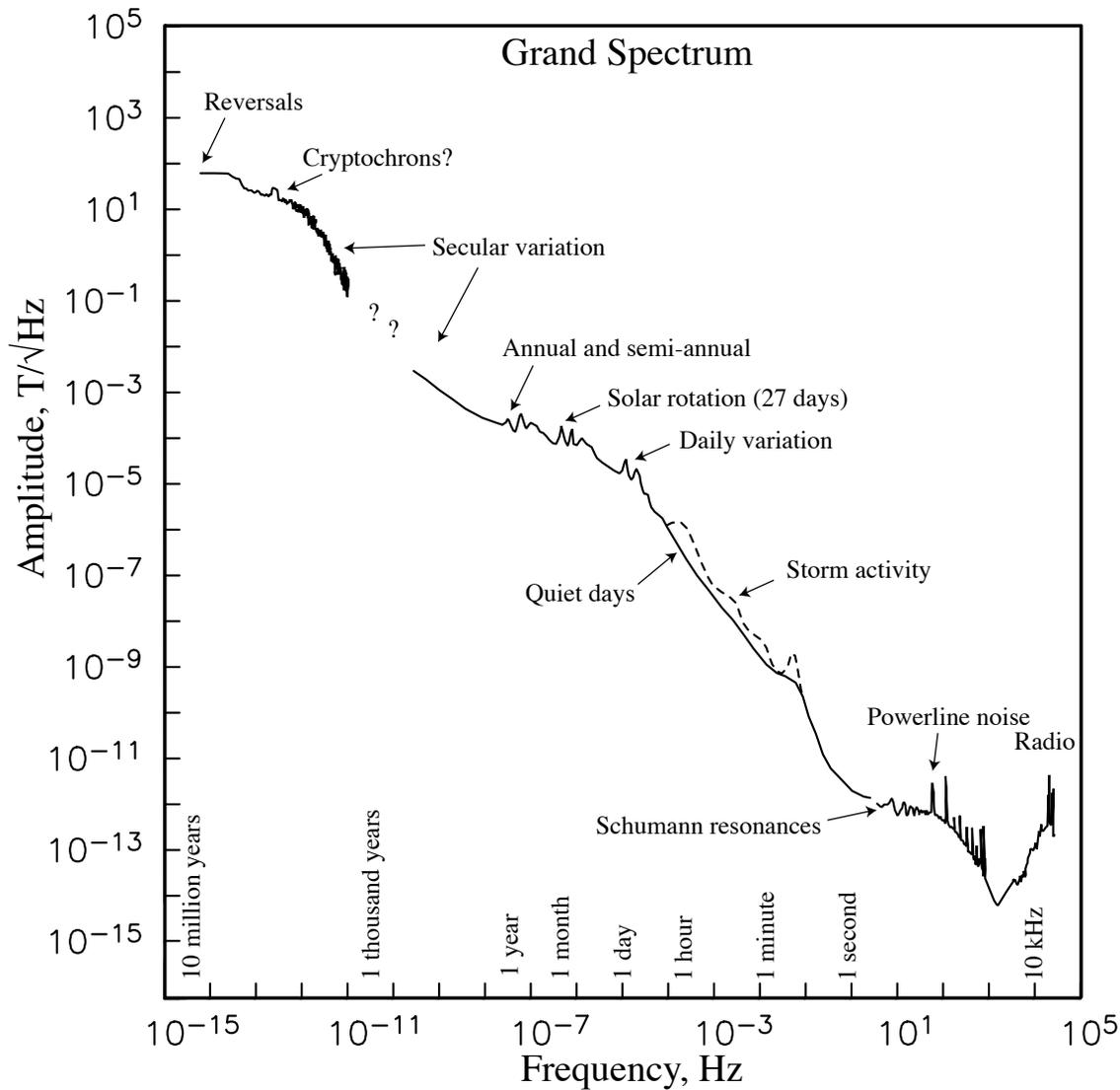
acts to oppose the main field and is also modulated by solar activity. Although changes in solar activity probably occur on all time scales the associated magnetic variations are much smaller than the changes in the core field at long periods, and only make a very minor contribution to the power spectrum.

With an adequate physical theory to describe each of the above processes one could predict the power in geomagnetic field variations as a function of frequency. The inverse problem is to use direct observations or paleomagnetic measurements of the geomagnetic field to estimate the power spectrum. Power spectral estimation is usually carried out using variants of one of the following well-known techniques: (1) direct spectral estimation based on the fast Fourier transform, and using extensions and improvements to the time-honored periodogram method introduced by Schuster in 1898 to search for hidden periodicities in meteorological data; (2) the autocovariance method which exploits the Fourier transform relationship between the time domain autocovariance and frequency dependent power spectral density of a process; (3) parametric modeling schemes like the maximum entropy method based on a discrete autoregressive process. The relative merits of these techniques have been widely discussed (see Constable and Johnson, 2005, or Barton, 1983, for the geomagnetic context), while all have been used in analyses of geomagnetic intensity and directional variations. It is generally acknowledged (*e.g.*, Percival and Walden, 1993) that direct spectral estimation combined with tapering and averaging of nearly independent spectral estimates can provide high resolution estimates and be used to optimize the unavoidable tradeoffs between variance and bias.

The parameter often chosen to represent the geomagnetic spectrum is the field strength at mid-latitudes, or a proxy form for times where it is not possible to obtain a direct measurement. This is the case for paleomagnetic time series derived from lacustrine or marine sediments which provide only directional information and/or relative intensity variations. Barton (1982) combined spectra from lake sediment directional paleomagnetic records with those from full vector data recorded at magnetic observatories and used periodogram analysis in the first attempt to provide an integrated power spectrum for periods ranging from less than a year to  $10^5$  years. Courtillot and Le Mouél [1988] merged Barton's result with other spectral estimates at longer and shorter periods extending the time scales from seconds to millions of years. They debated whether the result was compatible with an overall  $1/f^2$  spectrum, and concluded that it was too early to make such an inference.

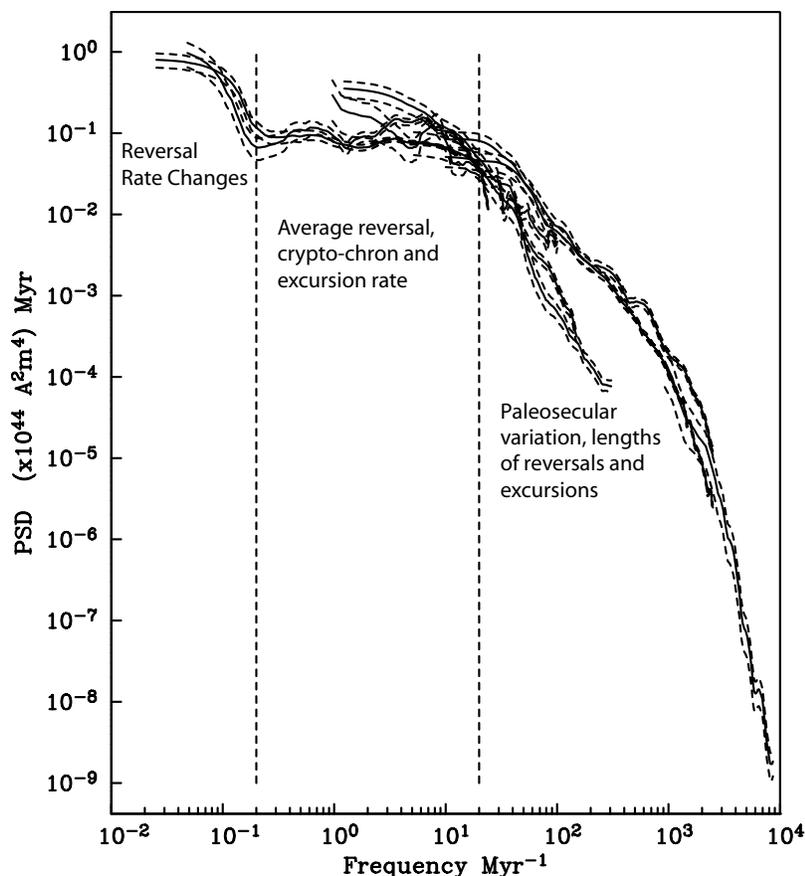
A recent version of such a composite spectrum (Constable and Constable, 2004) uses spectral estimates from relative paleointensity variations (Constable, Tauxe & Parker, 1998) at long periods and is shown in Figure 2 (note that this is an amplitude rather than a power spectrum, that is the square root of power spectral density). Between  $10^{-10}$  and 1 Hz, the spectrum is from Filloux (1987). Above 1 Hz, the results are those of Nichols *et al.* (1988). Internal variations reflecting motions of the fluid core dominate at periods longer than a few months, and the spectrum generally rises towards longer period (low frequency) with **reversals** (q.v.) of the dipolar part of the field the dominant influence on  $10^5$  to  $10^6$  year time scales. The eleven year sunspot cycle, solar rotation, and Earth's orbit modulate the distortions of the field associated with geomagnetic storms, which themselves have energy in the several hour to several second band. Energy at the daily variation and harmonics comes from diurnal heating of the ionosphere. Lightning creates high frequency energy in the Earth/ionosphere cavity, which resonates at 7–8 seconds and associated harmonics. At the highest frequencies there is presumed to be a continued fall-off in the natural spectrum. The upturn seen in Figure 2 reflects the dominant influence of man-made sources.

The spectrum in Figure 2 lacks information at very long periods where the spectrum is dominated by the intensity variations associated with changing geomagnetic reversal rate, and between about 10 kyr and 10 year periods, where the time scales for processes of internal and external origin overlap. Figure 3 provides a range of estimates at centennial to 50 Myr periods for the spectrum of the geomagnetic **dipole moment** (q.v.). The longest period power spectrum is estimated from reversal times given by the magnetostratigraphic time scale and shown in black. Further information comes from various sedimentary relative paleointensity records with varying accumulation rates and the dipole moment estimate of a time varying global paleomagnetic field model for the past 7kyr.



**Figure 2:** Composite amplitude spectrum of geomagnetic variations as a function of frequency (Constable and Constable, 2004): annotations indicate the predominant physical processes at the various timescales. Copyright American Geophysical Union, 2004, reproduced with their and the authors’ permission.

In constructing a paleomagnetic power spectrum like that in Figure 3 there are a number of challenges. A basic requirement for spectral analysis is a time series of observations, but there is no single record that covers the time span of interest. The magnetostratigraphic record appears to be non-stationary with long term changes in reversal rate, and provides no information about intensity variation on long time scales. The relative paleointensity records from sediments not only lack an absolute scale, but are usually unevenly sampled in time so that some stable calibration and interpolation scheme is required before using the standard analysis techniques. It is likely that some sediments record a smoothed version of the geomagnetic signal because of low sedimentation rates, while in others it may be necessary to consider the possibility of aliasing. Non-geomagnetic signals may be inadvertently interpreted as arising from geomagnetic variations with time.



**Figure 3:** Composite spectrum for the geomagnetic dipole moment constructed from the magnetostratigraphic reversal record with and without cryptochrons (frequencies  $10^{-2}$  to  $20 \text{ Myr}^{-1}$ ), various sedimentary records of relative paleointensity ( $10^0$  to  $10^3 \text{ Myr}^{-1}$ ), and from the dipole moment of a 0-7 ka paleomagnetic field model ( $10^3$  to  $10^4 \text{ Myr}^{-1}$ ). Figure redrawn from Constable and Johnson (2005).

The choice of dipole moment (as opposed to some other geomagnetic field parameter) is motivated in large part by the dominance of the geocentric axial dipole when the field is averaged over long time intervals: the strength of the axial dipole is representative of the global field, and may be related to the amount of energy required by the geodynamo or to the geomagnetic reversal rate. Although it is possible that other properties of the field (such as non-dipole field contributions) directly reflect particular physical processes controlling the secular variation, resolving such variations in paleomagnetic time series remains controversial. Overall, it is likely that the power in geomagnetic field variations is under-estimated.

There is substantial scope for improving the spectra in both Figures 2 and 3. Relative intensity records from sediments are steadily improving, and new modeling techniques may extend time-varying geomagnetic field models providing better dipole moment estimates on million year time scales. This may give new insight into what controls very long period secular variation. Many newer observations could be used for direct spectral estimates to replace the current schematic spectrum at periods from decades down to 1 second. Although the general form of the spectrum is quite well understood in this region, detailed analyses could provide further insight into the underlying physical processes. Techniques such as wavelet analysis, that can take account of non-stationarity in the underlying geomagnetic processes, have yet to be fully exploited for geomagnetic data (Guyodo *et al.*, 2000) and may prove useful. However, despite the relatively crude nature of existing spectral estimates it is apparent that the geomagnetic power spectrum does not follow a simple power law fall-off with increasing frequency. The form is instead influenced by the characteristic time scales that reflect the distinct physical processes contributing to the geomagnetic field.

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**Cross References** dipole moment; nondipole field; reversals; spherical harmonic model; inner core; outer core; mantle; crust; ionosphere; Sq currents; magnetosphere; Schumann resonances; secular variation; magnetospheric ring current