Matt Sprague

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How fast can Earth’s magnetic field reverse?

Introduction

The geodynamo, the outer-core convective circulation that produces the Earth’s magnetic field, has long been an active area of study. Despite our inability to observe it directly, researchers have produced numerous hypotheses about the nature of its mechanism, and particularly the circumstances that cause long-term variance in the magnetic field. The study of the geodynamo gives us various insights into other characteristics of the Earth system, such as the heat flux between the inner core and the mantle. The magnetic field also provides a very important role to life on Earth, by blocking solar wind particles and preventing dangerous disruption of essential electronics. The studies discussed in this review are mainly focused on determining mechanisms that may be responsible for the variability of Earth’s magnetic field.

This variability is primarily observed in polarity reversals and excursions. When a reversal occurs, the magnetic field gradually flips, switching the positions of the geomagnetic North and South poles on the Earth surface. The time period in which the planet’s polarity stays the same is defined as a *chron*, which vary in length from cryptochrons (anomalously short) to superchrons (anomalously long). Constable (2000) presents one model of reversals, with a typical chron length ranging from roughly 200 thousand to 2 million years, as shown in figure 1.

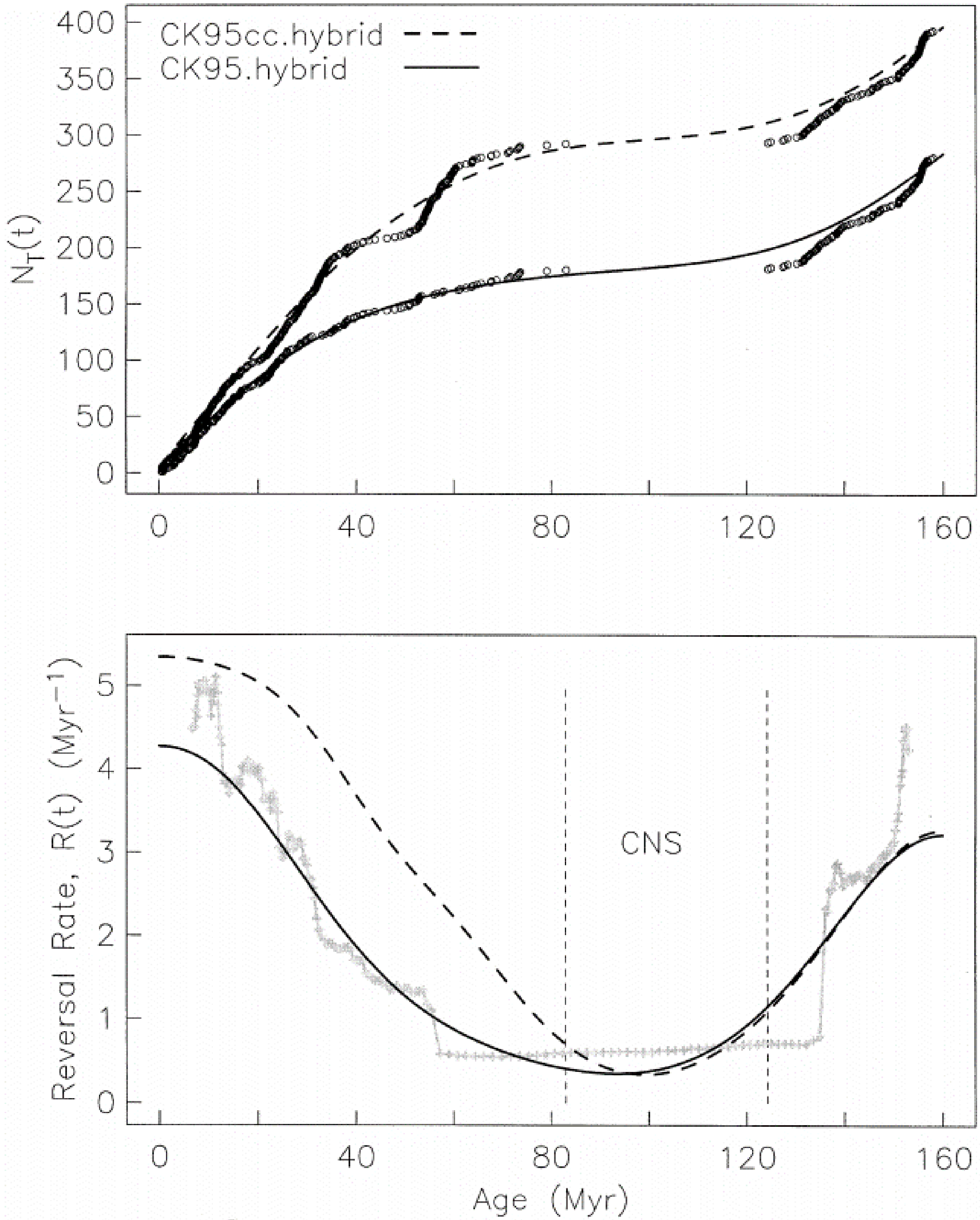

Figure 1: Above: modeled data of the cumulative number of reversals, $N_T(t)$, from the last 158 million years. Below: reversal rates, $R(t)$, during the same period. Formed from a combination of two different datasets of magnetic reversals, including cryptochrons (CK95cc.hybrid) or excluding them (CK95.hybrid). An inflection point of reversal rate is observed during the Cretaceous Normal Superchron (CNS), leading to a maximum at the present day. Source: Constable (2000).

Short of a full reversal, the magnetic field also experiences excursions, where one or both poles will meander across the globe without establishing a new polarity.

It is widely considered that the heat flux at the Core-Mantle Boundary (CMB) exerts an influence on the geodynamo (Hounslow et al., 2018). This is due to the nature of the geodynamo itself, which generates a magnetic field by convection of the fluid inner core. Because the mantle transports heat much more slowly, its long-term variations affect the convective patterns of the inner core, thus altering the geodynamo. The papers reviewed here discuss the patterns of this boundary heat flux and the extent of its effect on the inner core circulation.

Body

One proposed mechanism for controlling reversal frequency is that of mantle plumes. As described in Larson & Olson (1991), the Cretaceous Normal Superchron is one such example of a chron sustained by mantle plume activity. A mantle plume draws heat from great depths in the mantle toward a fixed point on the surface, typically producing volcanic hot spots. Larson & Olson explain that this increased heat flux allows for the outer core to conduct heat into the mantle at an elevated rate, which in turn heightens the convective activity in the core, strengthening the geodynamic engine and stabilizing the magnetic field. The authors compared the geomagnetic reversal time scale, from Harland et al. (1990), with a record of crustal mass production from mantle plume activity (figure 2). The ages of these landforms, as well as the geomagnetic time scale, were determined from the observation of magnetic anomalies of crustal material. In the proposed relationship, the rate of mantle plume production is inversely correlated with magnetic reversal frequency, hence increased plume heat flux acts to extend a chron timescale.

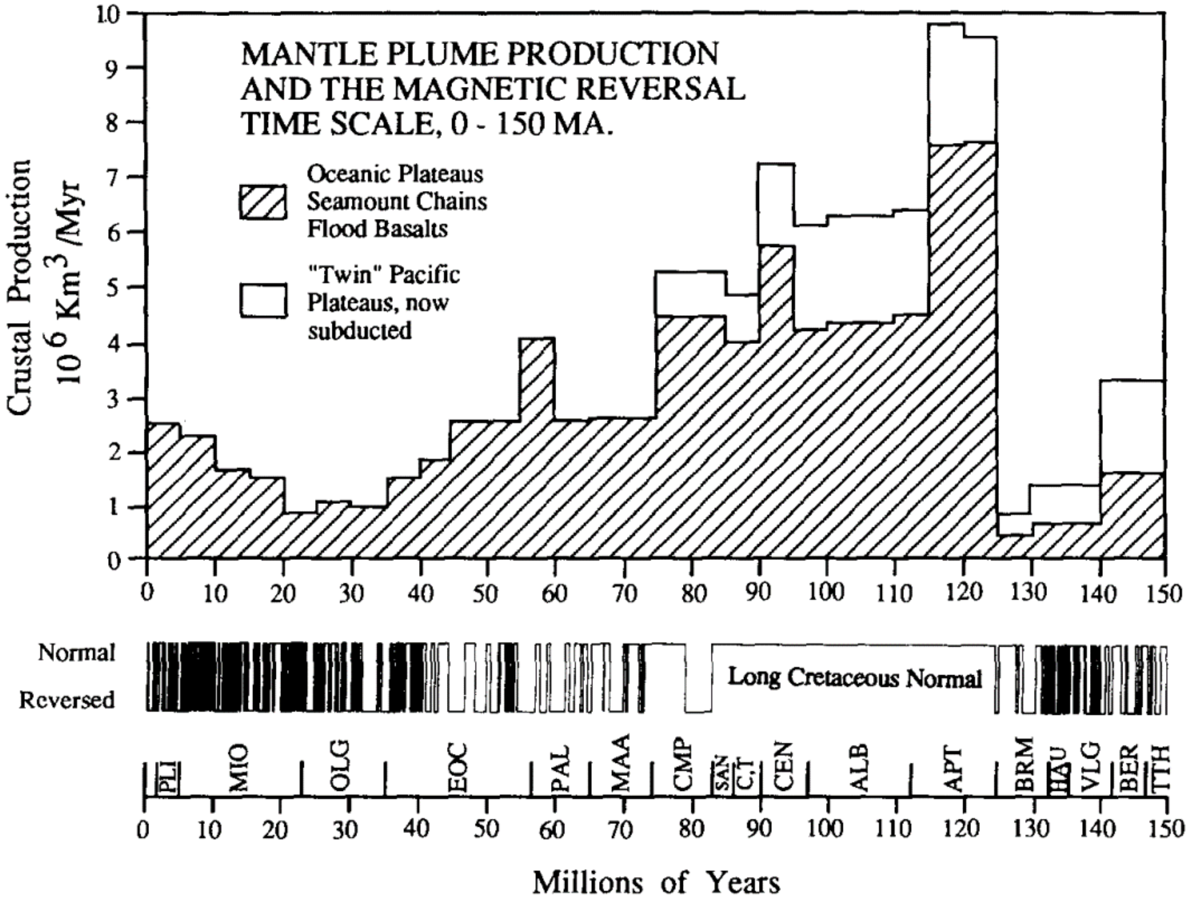

Figure 2: comparison of the rate of crustal volume production (above) with the geomagnetic reversal record (below), illustrating the proposed plume-geodynamo relationship. Source: Larson & Olson (1991).

Nonetheless, the mantle-plume hypothesis is largely incompatible with newer findings on the dynamics of the core-mantle boundary. As described below, other relationships have been proposed in more recent years, including the effect of thermal flux from continental subduction (Hounslow et al., 2018). Notably, Glatzmaier et al. (1999) propose that the thermal profile of CMB heat flux is more uniform than previously considered, which disputes the impact of heat flux at relatively localized mantle plumes.

Applying a modeling approach, Glatzmaier et al. (1999) considers several different patterns of CMB heat flux and models their effects on pole excursions, magnetic field strength, and reversals. The researchers tested 8 different cases. Some heat flux scenarios varied by latitude or longitude (cases A-F), while case H was based on real-world tomographic phenomena, and the most successful model, case G, applied a uniform heat flux. Based on this observation, Glatzmaier et al. present the argument that heat flux across the CMB is in fact more uniform than previously considered.

The structure of the CMB heat flux has been recorded with seismic tomography, the study of seismic wave velocities in the Earth's interior to determine differences in composition and temperature. The anomalies observed at the greatest depths of the mantle suggest that temperatures vary by hundreds of degrees Kelvin in different areas of the CMB (Su, 1994). In case h, the model ran based on this observed scenario, but the resulting magnetic excursions and aborted reversals are highly variable compared to the more realistic conditions observed in case g, shown in figure 3. Because case g provided the patterns that most closely mirror real magnetic field variation over time, Glatzmaier et al. argue that the CMB heat flux is more uniform than previously considered. The observed anomalies in seismic velocity could, in fact, be a result of compositional differences along the boundary, instead of variance in heat flux.

The paper's conclusions, however, are not comprehensive. The resulting time spans of magnetic field polarity are only 300 Kyr in length, due to constraints of computer modeling, thus there are too few reversals in each case to provide a statistical analysis of reversal frequency. Models of the geodynamo require a high temporal resolution in order to reliably capture patterns of variability. Advances in computing technology since 1999 have greatly improved the capabilities of geodynamo modelling, allowing for studies with high resolution and large timescale.

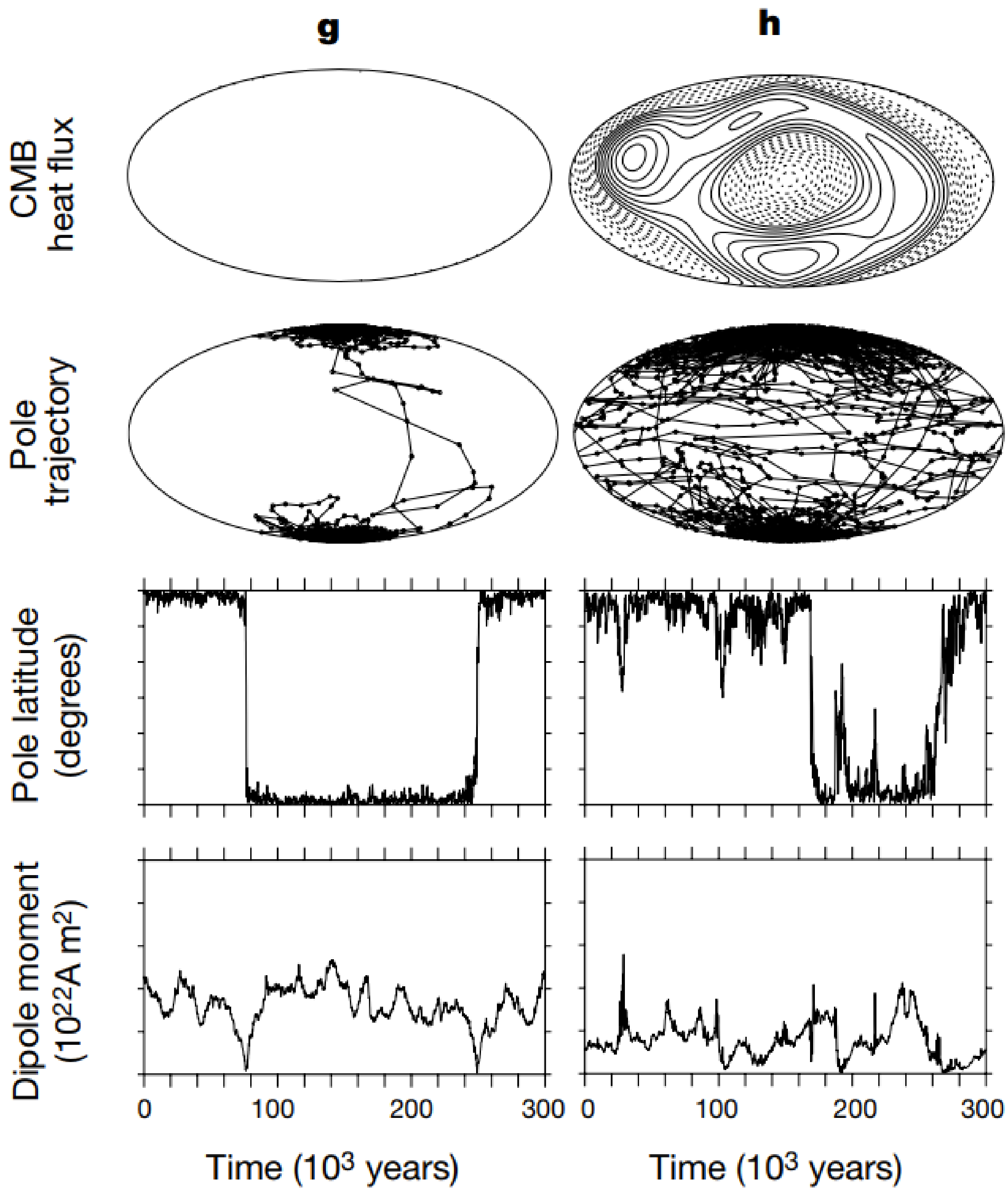

Figure 3: Selected cases g (uniform CMB heat flux) and h (based on seismic tomography), with inputted CMB heat flux patterns shown on a Hammer projection. Each case gives an associated trajectory of pole motion (with time resolution of about 100 years), a time series of pole latitude showing excursions and reversals, and the strength of the dipole moment over a span of 300 thousand years. Cases A-F omitted. Source: Glatzmaier et al. (1999).

Newer studies have addressed the question of reversal frequency with more extensive modeling efforts. Olson et al. (2010) applies some of the discussed CMB conditions to a model spanning 40 million years. In contrast to the mantle plume hypothesis, the study found that low heat flow (especially at the equator) would slow geomagnetic reversals, sustaining chrons for longer time periods. In the cases tested with tomographic flux conditions, increasing the amplitude of heat flow variability increased magnetic reversal frequency, but changes in the overall mean boundary flux had a larger effect. In addition, the poles tended to migrate along the longitudinal sections with the most heat flow. Meanwhile, the uniform CMB case had a lower frequency of reversals. Comprehensively, the model displayed that the reversal frequency is directly proportional to total CMB heat flux, to equatorial CMB heat flux, and to flux heterogeneity across the entire boundary. The findings also generally confirm that geodynamo patterns are not random: the total CMB heat flux only needs a change of about 20% to significantly influence the reversal frequency, which is stated to be reasonable given the variability of Earth phenomena such as plate subduction and magma production. The paper does not define any particular heat flow pattern to be the most realistic, but it does explain the variability of chron length as a function of CMB heat flux, arguing that decreases in total heat flow may have given rise to superchron events in the past.

Zhang & Zhong (2011) bring analysis of the Core-Mantle Boundary one step further by connecting its variability over time with tectonic conditions at the Earth surface. They employ three-dimensional modeling of mantle heat fluxes with an imposed tectonic plate motion model spanning the last 450 Ma, particularly to study the effect of the formation, existence, and breakup of the Pangea supercontinent. They also attribute a large effect to the equatorial heat flux compared to the global heat flux, based on the observation that the lowest equatorial fluxes coincide with the Kiaman and Cretaceous superchrons.

The model results produced surface heat fluxes accurate to the modern day. While the formation of the Pangea supercontinent did not significantly alter surface heat flux, it increased by about 16% from 190 – 120 Ma ago while plate motion occurred rapidly, and eventually settled back to a near-baseline value. The model also revealed that lithospheric subduction greatly influences both the pattern and amplitude of CMB heat flux. They observed CMB heat flow minima at 270 and 100 Ma before present, during the rifting of Pangea and the spreading of the separated continents across the ocean, respectively. Both of these time periods occur during notable superchrons, leading to Zhang & Zhong's hypothesis that equatorial heat flow is a driver of reversal frequency.

The relationship between continental subduction and magnetic reversals is more fully addressed by Hounslow et al. (2018). This study assesses a relationship between global subduction flux and geomagnetic reversal rate, finding a strong positive correlation with a ~120 Ma time lag between plate subduction and effect on reversals. This lag accounts for the travel time of a subducted slab's thermal footprint to the greatest depths of the mantle – its value lies within a wide range of estimates for this expected delay. The study notes that slab material likely takes 150-300 Ma to truly reach the CMB, but that the heat carried by the slab can introduce a convective cell that would exert a heat flux on the boundary much sooner, within 30-60 Ma.

For the purposes of the study, two different tectonic plate models were used; one model ("V15") included subduction area flux (SAF) from Vérard et al. (2015), while SAF was directly computed from the second model ("M16"). SAF describes the amount of plate area subducted per unit time, which was applied as a proxy to volumetric subduction flux. These model results agree with subduction estimates from real-world observation, such as the record of subduction magmatism. The subducted material was not assessed spatially in its effect on CMB heat flux, but rather the total global SAF was compared to geomagnetic reversal rates. The relationship, combined with the aforementioned time delay, produced a fairly robust positive correlation, confirming that subducting plates can in fact have a large impact on the geodynamo.

Conclusions

Although extensive research has addressed the functions of the geodynamo in producing the magnetic field, it is still a difficult task to accurately represent its mechanisms. Many studies are forced to rely primarily on models to estimate the frequency of geomagnetic polarity reversals, the strength of the magnetic field, and many variables associated with the geodynamo such as CMB heat flux. There is still room for improvement in our computing capability, which will either confirm old hypotheses or present unexpected conditions. Despite suggestions that CMB heat flux is uniform (Glatzmaier et al, 1999), most models still make assumptions based on observed variance in heat flow across the boundary. The geodynamo appears to be affected significantly by overall CMB heat flux, particularly in equatorial latitude bands, part of which is a result of tectonic plate subduction. Subducting plates can carry a thermal signature all the way to the boundary of the outer core, forcing thermal conditions that increase reversal rates. As noted by Hounslow et al. (2018), there are still uncertainties inherent in the tectonic subduction hypothesis, particularly the expected time lag between a subduction event and its effect at the greatest depths of the mantle. Resolving these questions will give much more reliable insight into the mantle conditions controlling geodynamo flux, particularly the conditions giving rise to extended superchrons.

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