Earth and Planetary Science Letters 388 (2014) 9–17

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Nonrandom geomagnetic reversal times and geodynamo evolution

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ARTICLE INFO

Article history:
Received 17 June 2013
Received in revised form 15 November 2013
Accepted 18 November 2013
Available online 13 December 2013
Editor: Y. Ricard

Keywords:
geodynamo
polarity reversals
Geomagnetic Polarity Time Scale
superchrons
Sherman's test

ABSTRACT

Sherman's ω-test applied to the Geomagnetic Polarity Time Scale (GPTS) reveals that geomagnetic reversals in the Phanerozoic deviate substantially from random times. For 954 Phanerozoic reversals, ω exceeds the value expected for uniformly distributed random times by many standard deviations, due to three constant polarity superchrons and clustering of reversals in the Cenozoic C-sequence. Reversals are nearly periodic in several portions of the Mesozoic M-sequence, and during these times ω falls below random by several standard deviations, according to some chronologies. Polarity reversals in a convection-driven numerical dynamo with fixed control parameters have an overall ω-value that is slightly lower than uniformly random due to weak periodicity, whereas in a numerical dynamo with time-variable control parameters the combination of superchrons and reversal clusters dominates, yielding a large ω-value that is comparable to the GPTS. Sherman's test applied to shorter Phanerozoic reversal sequences reveals two geodynamo time scales: hundreds of millions of years represented by superchrons and reversal clusters that we attribute to time-dependent core–mantle thermal interaction, plus unexplained variations lasting tens of millions of years characterized by alternation between random and nearly periodic reversals.

1. Introduction

Identifying the causes of time variability of geomagnetic polarity reversals is fundamental to understanding the geodynamo. The time between geomagnetic reversals varies over more than three orders of magnitude, from 40 Myr constant polarity superchrons to short chrons of a few tens of thousands of years (Ogg, 2012) and even shorter polarity excursion events lasting a few thousand years (Valet et al., 2008). This behavior contrasts with the solar dynamo, which reverses polarity regularly with each solar cycle, creating a nearly periodic 22-yr dynamo oscillation (Jones et al., 2010).

Because of their variability, most analyses of geomagnetic reversal sequences treat individual reversals as random events and seek a statistical characterization of their frequency. A standard approach is to compare the distribution of geomagnetic polarity chron lengths to well-known probability distributions, such as Poisson, gamma, or log-normal. There is a long-running controversy about which probability distribution best represents geomagnetic reversal sequences, and what it implies for the geodynamo (Naidu, 1971; Phillips, 1977; McFadden and Merrill 1984; 1997; Constable, 2000; Sorriso-Valvo et al., 2007; Ryan and Sarson, 2007; Vallianatos, 2011; Shcherbakov and Fabian, 2012).

Numerical dynamos offer a powerful tool for interpreting reversal sequences in terms of the fundamental dynamical processes that govern the geodynamo (Glatzmaier et al., 1999). Convection-driven numerical dynamos have been run for the equivalent of hundreds of millions of years in low resolution mode, producing continuous reversal sequences numbering in the hundreds (Wicht et al. 2009; 2010; Driscoll and Olson, 2011; Lhuillier et al., 2013). Direct comparisons have been made between histograms of chron lengths generated by numerical dynamos and the Poisson and other probability distributions (Lhuillier et al., 2013), between dynamo and geomagnetic reversal sequences in the time domain (Driscoll and Olson, 2011; Olson et al., 2013), and between individual geomagnetic and dynamo reversals (Amit et al., 2010; Olson et al., 2011), with fair agreement in some cases. Overall, the variety of reversals in these dynamos (Wicht and Olson, 2004; Aubert et al., 2008; Wicht et al., 2009; Olson et al., 2010) is comparable to the variety in the paleomagnetic record (Valet et al., 2012).

Reversals in numerical dynamos can be divided into three broadly defined categories, based on their sequencing. First, there are dynamos that produce sequences of regularly spaced reversals. Typically, these dynamos are rich in large-scale shear flows (Wicht and Olson, 2004). In this paper we use the term *periodic* for reversal sequences of this type, even though their polarity chrons are generally not precisely equal in length. Second, there are dynamos that produce seemingly random reversal sequences. Much of the kinetic energy in these dynamos is concentrated in

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0012-821X/$ – see front matter
http://dx.doi.org/10.1016/j.epsl.2013.11.038

smaller-scale convection (Aubert et al., 2008) rather than larger-scale shear flows. Reversal times in these dynamos appear to be uniformly probable (Lhuillier et al., 2013), although there may be inhibition for a short time immediately following a reversal (Wicht et al., 2010). We use the term *random* for reversal sequences of this type. The third category includes numerical dynamos with strongly modulated external forcing, such as time variable core–mantle boundary heat flow and variable rotation. These dynamos tend to produce reversal sequences modulated on the timescales of the external forcing (Driscoll and Olson, 2009b) and may show long intervals with stable polarity analogous to geomagnetic superchrons, as well as dense clusters of reversals. In conformity with previous studies (Jonkers, 2003; Carbone et al., 2006) we use the term *clustered* for reversal sequences of this type.

Here we analyze the entire Phanerozoic Geomagnetic Polarity Time Scale (GPTS) as well as Cenozoic and Mesozoic portions of the GPTS using Sherman's ω-test, finding evidence of periodic, random, and clustered behavior. We apply the same analysis to long reversal sequences from two convection-driven numerical dynamos, one with fixed (time-independent) control parameters, the other with modulated (time-dependent) control parameters that is meant to simulate the evolution of the geodynamo caused by changes in the dynamical state of the core. We show that the dynamo with modulated core parameters yields ω-statistics similar to the Phanerozoic GPTS, whereas the dynamo with fixed parameters does not.

2. Sherman's test for random times

Sherman (1950) proposed the following statistic to measure deviations from uniform spacing in a sequence of n events that occur at discrete times t_i:

$$\omega_n = \frac{1}{2\tau}\sum_{i=1}^{n+1}\left|x_i - \frac{\tau}{n+1}\right| \tag{1}$$

where x_i denotes the $n+1$ time intervals separating the events, and

$$\tau = \sum_{i=1}^{n+1} x_i \tag{2}$$

is the total duration of the record. Because the second term on the r.h.s. of (1) represents the average time interval, ω_n is a simple measure of how much the $n+1$ intervals deviate from their average length. In our application, t_i represent the reversal times (chron boundaries), x_i are the chron lengths, and τ is the length of the record under consideration.

Use of absolute values in the definition of statistical parameters often causes mathematical problems, but in this case Sherman (1950; 1957) has shown that the moments and percentiles of (1) can be calculated in finite terms. In particular, the mean μ_n and the variance σ_n^2 of ω_n for n uniformly distributed random events are given by

$$\mu_n = \left(\frac{n}{n+1}\right)^{n+1} \tag{3}$$

and

$$\sigma_n^2 = \frac{2n^{n+2} + n(n-1)^{n+2}}{(n+2)(n+1)^{n+2}} - \left(\frac{n}{n+1}\right)^{2n+2} \tag{4}$$

respectively. For a large number of events ($n \gg 1$), (3) and (4) simplify to

$$\mu_n \simeq e^{-1} \tag{5}$$

and

$$\sigma_n^2 \simeq \frac{2e-5}{ne^2}, \tag{6}$$

respectively. In this same limit, the standardized variable

$$\omega_n^* = \frac{\omega_n - \mu_n}{\sigma_n} \tag{7}$$

approaches a Normal distribution with zero mean and variance one. According to (1), the range of ω_n is given by

$$0 \leqslant \omega_n \leqslant \frac{n}{n+1}, \tag{8}$$

the lower limit of $\omega_n = 0$ corresponding to events that are equally spaced in time, and the upper limit of $\omega_n = 1$ corresponding to $n \gg 1$ events that are tightly clustered in time. Uniformly random times yield a value of $\omega_n = 1/e \simeq 0.3679$ for $n \gg 1$, according to (3) and (5).

The clear separation between the limiting values of ω_n provides a straight-forward way to analyze and interpret reversal sequences in the GPTS and numerical dynamos, by classifying reversal sequences as periodic (nearly equal chron lengths and $\omega_n \ll 1/e$), uniformly random (moderately variable chron lengths and $\omega_n \simeq 1/e$), or clustered (extremely variable chron lengths and $\omega_n \gg 1/e$). Furthermore, likelihoods can be assigned to these classifications using (3) and (4), even for sequences with a relatively small number of reversals. In Appendix A we give exact and approximate expressions for calculating P, the percentiles of Sherman's ω that correspond to uniformly random times, along with tabulated values of P for small and moderate sample sizes n.

3. Sherman's test applied to Phanerozoic reversals

Fig. 1 shows the sequence of geomagnetic reversals for the Phanerozoic Eon from Ogg (2012), in terms of the polarity, the five million year running average reversal rate, and the average polarity bias ($f_N - f_R$), where f_N and f_R denote the fraction of time spent in normal and reverse polarity, respectively. The Phanerozoic reversal record is known to be incomplete, particularly in the Paleozoic, and in addition, there are uncertainties in the timings of individual reversals, especially those older than the Cenozoic C-sequence (Cande and Kent, 1995; Ogg, 2012). Accordingly, we also analyze two other recent compilations of Mesozoic M-sequences (Tominaga and Sager, 2010; Malinverno et al., 2012). Table 1 gives n, ω_n, ω_n^* and P for the five GPTS sequences considered.

For the 0–542 Ma Phanerozoic GPTS, we find $\omega_n = 0.558$. For $n = 954$ random times, $\mu_n \simeq 1/e$ and $\sigma_n \simeq 7.9 \times 10^{-3}$, so the Phanerozoic ω is about 24 standard deviations above random, as Table 1 shows. The primary cause of the anomalously large ω in the Phanerozoic is the slow modulation in reversal frequency evident in Fig. 1, and in particular, the three constant polarity superchrons, the Cretaceous Normal Superchron (CNS) at 83–125 Ma, the Kiaman Reversed Superchron (KRS) at 267–314 Ma, and the Moyero Reversed Superchron (MRS) at 463–482 Ma (Pavlov and Gallet, 2005), intervals devoid of (or nearly devoid of) reversals that are far too long to have occurred by chance alone. This inference is fully consistent with previous interpretations of reversals as outcomes of a Poisson or a gamma process. For example, if we were to assume that geomagnetic reversal times obey either Poisson (Phillips, 1977) or gamma statistics (McFadden, 1984) with a mean reversal rate of 2 per million years, then it is easy to show that the likelihood of three constant polarity superchrons occurring within the Phanerozoic by chance alone is vanishingly small.

The statistics in Table 1 also reveal that geomagnetic reversals deviate from uniformly random times away from the superchrons. For example, Table 1 shows that $\omega_n = 0.409$ for GPTS reversals