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Is Earth's magnetic field reversing?

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Abstract

Earth's dipole field has been diminishing in strength since the first systematic observations of field intensity were made in the mid nineteenth century. This has led to speculation that the geomagnetic field might now be in the early stages of a reversal. In the longer term context of paleomagnetic observations it is found that for the current reversal rate and expected statistical variability in polarity interval length an interval as long as the ongoing 0.78 Myr Brunhes polarity interval is to be expected with a probability of less than 0.15, and the preferred probability estimates range from 0.06 to 0.08. These rather low odds might be used to infer that the next reversal is overdue, but the assessment is limited by the statistical treatment of reversals as point processes. Recent paleofield observations combined with insights derived from field modeling and numerical geodynamo simulations suggest that a reversal is not imminent. The current value of the dipole moment remains high compared with the average throughout the ongoing 0.78 Myr Brunhes polarity interval; the present rate of change in Earth's dipole strength is not anomalous compared with rates of change for the past 7 kyr; furthermore there is evidence that the field has been stronger on average during the Brunhes than for the past 160 Ma, and that high average field values are associated with longer polarity chrons. There is no evidence from recent millennial scale time-varying paleofield models to indicate that the field is entering a polarity transition. Nevertheless, it remains a reasonable supposition that the magnetic field will eventually reverse even though the time scale is unpredictable. A more immediate concern is that ongoing secular variation in the magnetic field may be expected to moderate the current high dipole strength on centennial to millennial time scales: it would not be surprising if it dropped substantially, returning closer to the average without necessarily reversing. This could have important consequences for space weather, and also highlights the need for improved understanding of the impact of geomagnetic field strength on the production rates of cosmogenic isotopes that are used to estimate past solar variability.

Keywords: geomagnetic field; reversals; paleointensity; dipole moment; paleomagnetosphere

1. Introduction

Reversals of the geomagnetic field are a well-documented phenomenon known to have occurred throughout much of Earth's history [1]. The interval between reversals is highly irregular, and appears to change over time, with long periods (10's of millions of

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Table 1
Jargon Box

- Local paleomagnetic measurements of the direction $\hat{\boldsymbol{b}}$ and strength B of the vector magnetic field $\boldsymbol{B}(\boldsymbol{s})$ are often expressed in terms of an equivalent virtual geomagnetic dipole $\boldsymbol{V}(\boldsymbol{s})$ located at the geocenter. They are related by $\boldsymbol{V}(\boldsymbol{s}) = R(s,\theta,\phi)\boldsymbol{B}(\boldsymbol{s})$ with R at a location with radius s, colatitude θ, and longitude ϕ given explicitly by

$$R(s,\theta,\phi) = \frac{4\pi s^3}{\mu_0}\begin{pmatrix} -\cos\theta\cos\phi & \sin\theta & \frac{1}{2}\sin\theta\cos\phi \\ -\cos\theta\sin\phi & -\cos\theta & \frac{1}{2}\sin\theta\sin\phi \\ \sin\theta & 0 & \frac{1}{2}\cos\theta \end{pmatrix}$$

- A *virtual geomagnetic pole (VGP)* is $\hat{\boldsymbol{v}} = \boldsymbol{v}/|\boldsymbol{v}|$ and gives the unit vector whose geographic coordinates on Earth's surface correspond to the north pole of the geocentric dipole that would generate the observed local field direction.
- A *geomagnetic excursion* occurs when VGPs lie more than 45° from the geographic axis.
- A *geomagnetic reversal* occurs when the field reverses polarity. VGPs migrate from positions in the vicinity of the north (or south) geographic pole to the opposite hemisphere pole.
- The *virtual dipole moment (VDM)* is $V = |\boldsymbol{V}| = \frac{2\pi s^3}{\mu_0}B(1+3\cos^2 I)^{\frac{1}{2}}$: I is the inclination of the local magnetic field vector.
- The *virtual axial dipole moment (VADM)* is $V_A = \frac{2\pi s^3}{\mu_0}B(1+3\cos^2 I_A)^{\frac{1}{2}}$: This is like the VDM, but I_A is the inclination expected from a geocentric axial dipole at the site, calculated from the site latitude λ via $\tan I_A = 2\tan\lambda$. Finding V_A does not require knowledge of paleofield direction.
- *Brunhes polarity interval* is the time since the last documented full reversal of the geomagnetic field at 0.78 Ma.
- The *tangent cylinder* is an imaginary cylinder, parallel to Earth's rotation axis, with sides tangent to the inner core boundary, interpreted as dividing convection regimes in Earth's core. If continued upwards the cylinder would intersect Earth's surface at a latitude of 79°.
- The *magnetic induction equation* describes time variations $\partial_t \boldsymbol{B}$ in the magnetic field in Earth's core, where $\eta = 1/\mu_0\sigma$ is magnetic diffusivity, σ is the electrical conductivity of the core, and $\boldsymbol{u}$ the fluid velocity,

$$\partial_t \boldsymbol{B} = \eta\nabla^2\boldsymbol{B} + \nabla\times(\boldsymbol{u}\times\boldsymbol{B}).$$

years) of uniform polarity interspersed with times of more frequent polarity changes. On average the field has reversed polarity about every half million years for the time interval 0–160 Ma. The current reversal rate is about 3.7 Myr^{-1} [2] depending on how one is counting, and the last reversal was at 0.78 Ma [3] suggesting at first glance that the next one may be overdue. The geomagnetic field strength (see Fig. 1), and in particular the dipole moment, has been decreasing for the past two centuries, and the rate is high compared with that expected for decay by diffusion. This has led to speculation [4,5] that the field may be in the initial

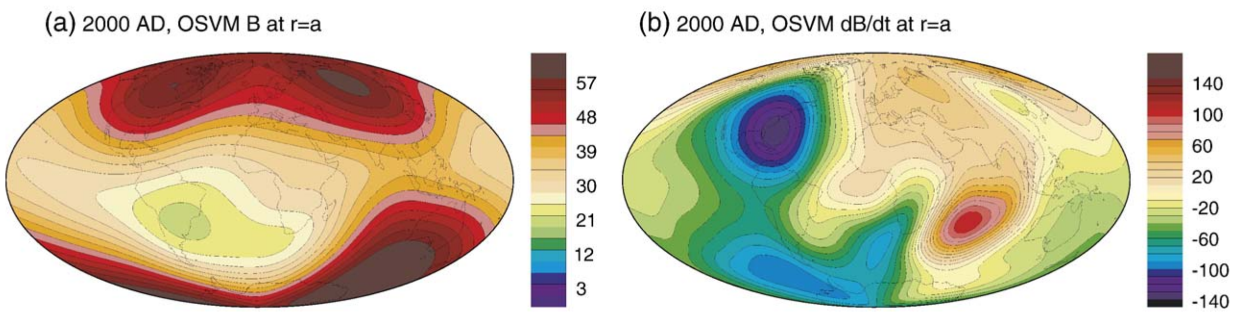

Fig. 1. (a) The magnetic field intensity in μT at Earth's surface for the epoch 2000, and (b) its rate change of change in nT yr^{-1}. Both are from the Ørsted secular variation model of [76].

stages of a geomagnetic reversal, and increased efforts to understand the nature of geomagnetic reversals using numerical dynamo simulations. If a reversal really is starting it would have a considerable impact, as the presence of a stable geomagnetic field is of more than academic interest to paleo and geomagnetists. Studies of the magnetic field (or absence thereof) on Earth and other planets indicate the important role it plays in maintaining our atmosphere, shielding us from the effects of cosmic rays and space weather, and preventing loss of volatile materials [6], and suggesting that the presence of a magnetic field may be a vital constituent of a habitable environment here on Earth.

In this work we first introduce some necessary terminology and consider what we might expect to observe as a field reversal occurs. The time scale derived from marine magnetic anomaly data is then used to examine whether a reversal should be considered overdue. The limitations intrinsic to such an approach are discussed.

We assess recent magnetic field changes in the longer term context of typical paleomagnetic variations. The discussion brings together modern and historical magnetic field observations (which can provide accurate and detailed models) and magnetostratigraphic and other paleomagnetic data, which span the necessary long time scales but inevitably have much poorer resolution. Numerical simulations are beginning to play a role in our expectations of what will happen during a reversal, and we discuss the likely impact of changes in the dipole moment on space climate and the external magnetic field.

2. Virtual geomagnetic poles and virtual (Axial) dipole moments

When it is not in a transitional state the geomagnetic field can be represented to first order by that of a dipole placed at Earth's center. This representation is an entrenched part of paleomagnetic analyses (even when the field is reversing), so that it is common for measurements of the magnetic field to be expressed in terms of equivalent virtual geomagnetic pole (VGP) positions for directions and either by virtual dipole moments (VDMs) or virtual axial dipole moments (VADMs) for field strengths. The path followed by VGPs during a reversal is often used to describe individual transitional records. VGPs, VDMs and VADMs and some other terms relevant to our discussion are defined in Table 1. For our purposes it is important to note that, although VGPs, VADMs and VDMs are widely thought of as representations that approximate the geomagnetic field as a dipole, they are simply linear transformations of the local magnetic field vector, and still contain all the nondipole contributions to the magnetic field. They can thus be used to describe any geomagnetic field structure whether or not it is predominantly dipolar, although the interpretation of the non-dipolar field contributions is less obvious than for a dominantly dipolar field.

3. What happens during a reversal?

A normal to reverse (or reverse-normal) polarity transition occurs when the north (south) pole of the predominantly dipolar geomagnetic field moves from its current position near Earth's rotation axis in the northern hemisphere to an equivalent location in the southern hemisphere. Transitions are generally described in terms of changes in field strength or VADMs and/or the paths followed by VGPs over time. Many paleomagnetic records have only directional or intensity observations rather than the full magnetic vector; the temporal sampling can also be sporadic or overly smoothed by sedimentation processes. Despite persistent efforts to study the phenomenon paleomagnetic data provide only a sketchy view of what happens during a geomagnetic reversal (e.g. [7,8]). Nevertheless, several points of consensus have emerged from detailed studies of transitions recorded in lava flows and sediments.

It is widely accepted that during a reversal the predominantly dipolar geomagnetic field undergoes a decay, and that the field strength can be as low as 10–20% of what we see today. Transitional magnetic fields are non-dipolar in structure since the tracks followed by VGPs vary with the location of the paleomagnetic record [9]. The time between reversals is highly variable, and there is evidence that the length of the transitional period also varies with location: most recently Clement [10] has noted that reversals recorded in marine sediments appear to take longer at high latitudes. Such variations in length may in part reflect the lack of a clear diagnostic valid at a range of individual locations that can indicate when the field is irrevocably committed to reversing, and the fact that diminished intensity often persists for longer than the associated directional changes. Even when the reversal is complete it can be difficult to identify the part of the record in which the field is actually reversing. The time taken for a reversal is usually considered to be some thousands of years [8], although numbers as small as 100 yr and greater than 20 kyr have been cited [7]: numerical simulations also indicate lengths that vary with geographic location, along with the possibility that extended periods of low field strength may prolong the reversal process and reflect conditions that hinder re-establishing a stable polarity field [11,12]. The idea that the apparent reversal length can vary with location is generally accepted, although the wide range cited above for transition times may be more of a stretch.

Several other kinds of paleomagnetic observations may also be considered relevant to the question of whether the field is about to reverse, although for many researchers their interpretation remains controversial.

There is a tendency for VGP paths to occupy preferred meridional swaths that seem to correlate with structures observed in the modern geomagnetic field [13,14] and have been interpreted by some to reflect the influence of the CMB on reversal paths (see also [15]). Others have argued that these are artifacts generated by non-uniform sampling locations, and the inadequacies of the rock magnetic record (e.g. [16]). It has been widely noted that one of the longitudinal swaths coincides with the region in Fig. 1(b) where the field is changing most rapidly, and with the South Atlantic anomaly, the area of lowest field strength in Fig. 1(a). When the field is downward continued to the core–mantle boundary (using the approximation that magnetic sources in the mantle can be neglected), the South Atlantic anomaly corresponds to a region of reverse polarity flux. It has been proposed that a region like this could play an important role in the reversal process, growing and migrating polewards to overcome the present dipole field and eventually cause it to regenerate in the opposite direction [17].

A second difficult issue concerns the relationship between geomagnetic excursions and reversals. Geomagnetic excursions are brief (geologically speaking) intervals when the magnetic field departs from its stable configuration of dipole dominance. In the paleomagnetic record they are characterized by low field strengths, and field directions that deviate considerably from that expected from a geocentric axial dipole (usually VGPs lying more than 45° from the rotation axis). Excursions are more difficult to document than reversals. Although the typical time frame for the anomalous field behavior may not be very different from a reversal, the field returns to the same initial state, making excursions easy to miss in many geological environments. Nevertheless, they appear to be an important component of geomagnetic field variability.

A large number of excursions (more than 10) have been reported during the Brunhes [18–20]. Most of the records come from sediments ([21], recently noted the existence of only a handful of well-documented volcanic records), and the resolution of the sedimentary records is variable and often limited by the accumulation rate or other features of the sedimentary environment. Lund et al. [20] note that when characterized by directional anomalies, individual excursions appear to last 1–2 kyr, but that they tend to occur in clusters of two or three with intervening intervals of large amplitude secular variation, and the cluster of excursions can last 20–50 kyr. In later work on the best documented recent excursion (the Laschamp which occurred at around 41 ka) Lund et al. [22] distinguish class I and class II excursions on the basis of patterns seen in the directional spatial variability. They suggest that class I excursions are like enhanced secular variation in terms of departure from dipole axis, may be limited to regions of the order of 5000 km in size, and could be what is expected from secular variation at times of low dipole moment. This classification seems to carry with it the supposition that the axial dipole part of the field retains its initial polarity, but is diminished in magnitude: in this sense the regional excursion could be thought of as an accidental local reversal giving rise to anomalous directions, and need not necessarily be considered a prelude to magnetic field reversal. Class II excursions lack the large open loops seen in VGP paths for Class I, and are typified by abrupt

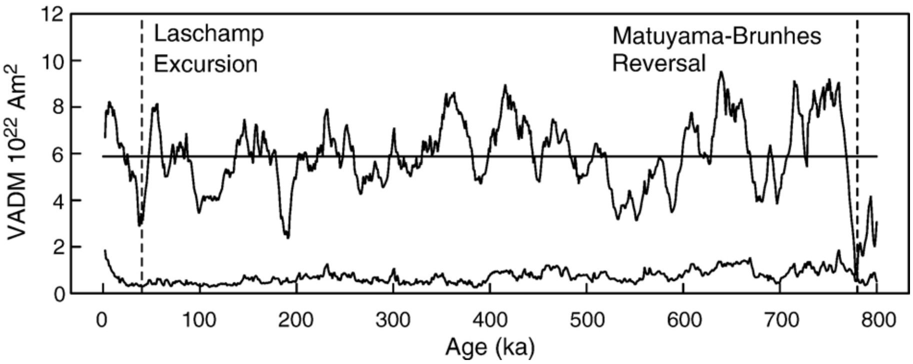

Fig. 2. SINT800 VADM record for the past 800 kyr derived from stacked and averaged marine sediment records ([77]).

in phase changes in directions, followed by static clustering of anomalous directions, and in phase return to normal directions. A complicating factor is that the Laschamp appears to demonstrate both class I and class II behavior in different geographical regions (mid to low latitudes versus polar regions respectively). In some other regions there are no excursional directions during the Laschamp, just low field intensities: this might be a consequence of low sedimentation rates resulting in low temporal resolution of directional variation. Large regional differences in spatio-temporal field variations also feature in both historical and millennial time-varying field models (e.g. [23,24]). In principle it is possible that Class II excursion records might be grouped with those reversal records that tend to occupy preferred meridional swaths, and class I excursions with those that show more complex structures.

The exact number of excursions during the Brunhes is still not well-defined, nor their relationship to reversals, although a widely held view is that excursions and reversals are part of a continuum of geomagnetic field behavior that reflect expected magnetohydrodynamic fluctuations in Earth's core, and that there may be no specific triggers or special physical circumstances that pertain to geomagnetic reversals. If excursions are to be considered equivalent to reversals then these short events (which certainly are more frequent and may occur more regularly than full reversals) will be needed to characterize the real recurrence time for reversals, but there remains the possibility that the duration of an excursion will be shorter than that of a full reversal. Gubbins [25] has suggested that a reversal may be an excursion that successfully enters the inner core, and thus has a longer characteristic time associated with magnetic diffusion processes there.

Another observation not universally accepted (e.g. [26]) is the suggestion of sawtooth intensity variations during polarity epochs spanning the past 4 Myr [27], with the field rebounding to paleointensity highs shortly after a reversal, followed by an irregular gradual decrease toward the next reversal. This would suggest a quasi-deterministic component to the occurrence times of reversals. It is difficult to ascertain the relevance of this observation for the current epoch. Fig. 2 shows the SINT800 global estimate of dipole moment variations over the past 800 kyr, which spans the whole of the Brunhes. In contrast to earlier polarity epochs during 0–4 Ma, there is no systematic decrease to suggest that a reversal might be imminent. The current dipole moment is nearly as high as in the time interval immediately after the Matuyama–Brunhes reversal. Valet et al. [28] have recently extended the SINT 800 record of the VADM to 2 Ma, and studied the behavior surrounding reversals that occurred in this time interval. They note that there is typically a gradual decrease in VADM over a time interval of about 60–80 kyr preceding each reversal, and that the reversal itself is followed by a rapid large recovery, and speculate that diffusive processes dominate the pre-reversal episode, while induction drives the recovery. Such behavior has not so far been noted in numerical simulations.

We infer from the above discussion that factors that might be used to determine whether the geomagnetic field is entering a reversal include the amount of time since the last event (to be discussed in more detail in the next section), the current decay of field strength and its

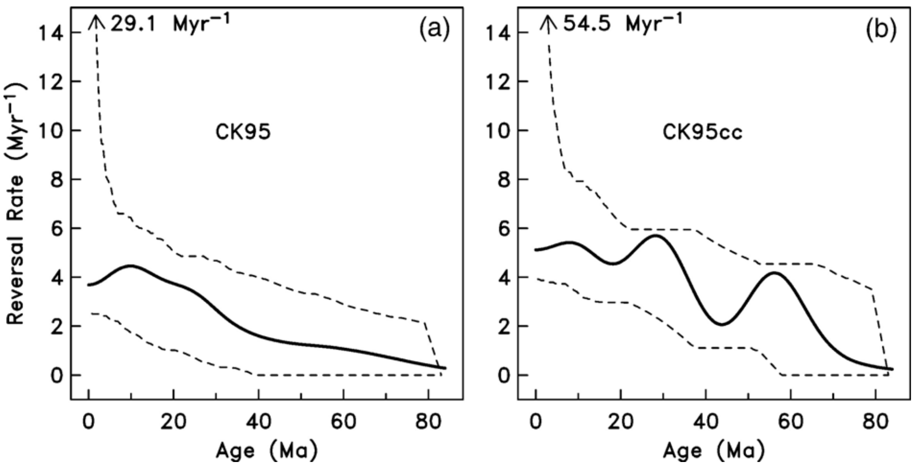

Fig. 3. Reversal rates as a Poisson process. Geomagnetic reversal rates for 0–84 Ma, as determined by [2] using the time scale of [3]: (a) CK95, cryptochrons excluded, (b) CK95cc, cryptochrons included. Solid line gives rate estimate, dashed lines give point-wise conservative upper and lower 95% confidence bounds under the assumption that reversals are a Poisson process with monotonic rate change from 84 Ma to present.

rate in comparison with what might be considered normal, and any systematic increase in complexity of the field compared with that expected from a dipole.

4. The past record of geomagnetic reversals and related events: is the next reversal overdue?

First order arguments about the probability of an imminent field reversal can be obtained from the geomagnetic polarity time-scale inferred from marine magnetic anomalies (e.g. [3]). The irregular occurrence times for reversals have traditionally been described by a Poisson or gamma renewal process with a time-varying rate [29], whereby reversals are treated as statistically random events. Most estimates of the occurrence rate increase from the end of the Cretaceous Normal Superchron (CNS, ~83–118 Ma BP) to a maximum of about 4.3 Myr^{-1} approximately 9 Myr ago, then decreased slightly to a current average value of about 3.7 Myr^{-1}, but the 95% confidence bounds on the time-varying rate are broad (Fig. 3(a); [2]). For the most recent epoch and the time scale of Cande and Kent [3], the upper and lower bounds on reversal rate are 29.1 and 2.5 Myr^{-1}, respectively. Given these rates and the assumption that a Poisson process provides a viable statistical description of reversal timings, we can infer the associated probabilities of observing a polarity epoch as long or longer than the current Brunhes epoch which has already lasted for 0.78 Myr. Table 2 shows that the probability is not improbably low unless we adopt a high value for the reversal rate. Most would consider the upper bound of 29.1 Myr^{-1} implausibly high, however, a lower value of this upper bound could only be justified if one were to place further limits on the allowed changes in reversal rate (see [2] for details). Similarly, a probability of 0.15 is obtained if one just considers the average reversal rate derived from the distribution of polarity interval lengths over the period 0–84 Ma (Fig. 4). The distribution has a high variance with 50% of all the polarity intervals shorter than 0.24 Myr, and only 14.7% longer than the current duration of 0.78 Myr.

Table 2
Reversal rates and probabilities

Time-scale	Method	Rate (Myr^{-1})	Current interval (Myr)	Probability
CK95	Lower bound	2.5	0.78	0.14
	Preferred estimate	3.7		0.06
	Upper bound	29.1		10^{-10}
	Average	2.2		0.15
CK95cc	Lower bound	3.9	0.49	0.15
	Preferred estimate	5.1		0.08
	Upper bound	54.5		10^{-12}
	Average	3.5		0.18

Estimates of the probability for a polarity chron as long or longer than the current one, assuming that reversals are generated by a Poisson process with the specified rates. The rates and chron lengths used are for the time scales without (CK95) and with cryptochrons (CK95cc). The preferred estimate with upper and lower bounds are for today's reversal rate (Fig. 3), while the average is just the mean rate for the past 83 Ma.

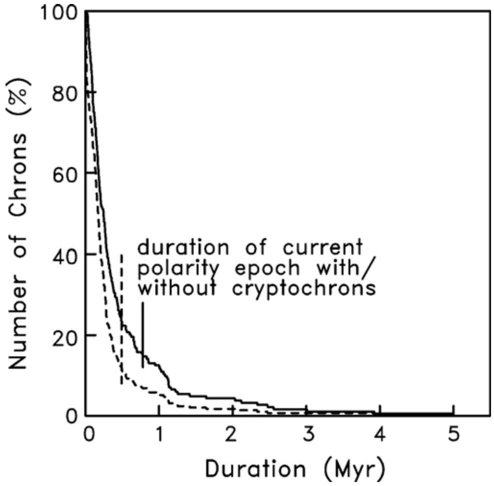

Fig. 4. Reversal statistics. Solid line is the total number of chrons in percent by minimal duration for the past 83 Myr, based on the time scale of [3]. Dashed line is the same including cryptochrons.

These results apply for firmly established reversals, but there are many geomagnetic events whose origin is less clear. These include both the cryptochrons found in the limited resolution marine magnetic anomaly records [3], and the more numerous geomagnetic excursions now documented for the Brunhes epoch [18,20]. Cryptochrons are considered to be very short polarity intervals [30] or intensity fluctuations [31,32] perhaps associated with excursions [33]. When they are included in the analysis, 50% of all polarity intervals of the past 83 Myr are shorter than 0.17 Myr. A cryptochron of reverse polarity is reported for the interval 0.49 to 0.50 Ma, thus the duration of the present polarity epoch decreases to 0.49 Myr, the current rate increases slightly, and the confidence bounds on reversal rate broaden further (Fig. 3(b)). But as seen in Table 1, the probabilities for a polarity interval this long remain similar to those found for the well-established reversals.

Only 12% of polarity epochs have been longer than 0.49 Myr. If the reversal record is complete, the most recent chron lasting longer than the current duration occurred around 10.4 Myr ago, when a normal polarity chron persisted for 1.029 Myr. It is worth noting that it occurs when average reversal rates are highest, and that a reverse polarity chron around 1.4 Myr ago also lasted 0.7 Myr. The situation does not change significantly when cryptochrons are included. A reverse polarity chron of 0.56 Myr duration is reported at around 1.4 Myr ago and a normal one of 0.46 Myr duration around 2.8 Myr ago.

The results summarized in Table 2 show that a polarity interval as long as the current one will occur 6–18% of the time if one considers average or lower bounds on the reversal rates. These results would suggest that the next reversal is bordering on overdue if one adopts a fairly conventional view and considers a probability of .05 as significant. But the current length would not be considered highly improbable under the Poisson model. For the upper bounds on rates an interval as long as either 0.49 or 0.78 Myr is extremely unlikely. It is possible that an estimate as high as 20 Myr^{-1} might yet apply if one considered every excursion in the Brunhes to count as the same kind of event as a reversal. In that case one would have to consider the most recent event as one of the Laschamp or Mono excursions [34], and the associated rates and interval lengths would then change correspondingly. More problematically, if we consider reversals and excursions an integral part of secular variation as discussed in Section 3, it would invalidate the simple Poisson probability model used here, and this highlights the need for a more sophisticated approach in which reversals are treated as part of the continuum of magnetic field variability rather than as random events with no temporal covariance or memory of the associated physical process. Although some attempts have been made in this direction, allowing for either recovery or dead time between successive reversals [35], these have not yet taken account of the large scale fluctuations in geomagnetic field strength that are known to occur

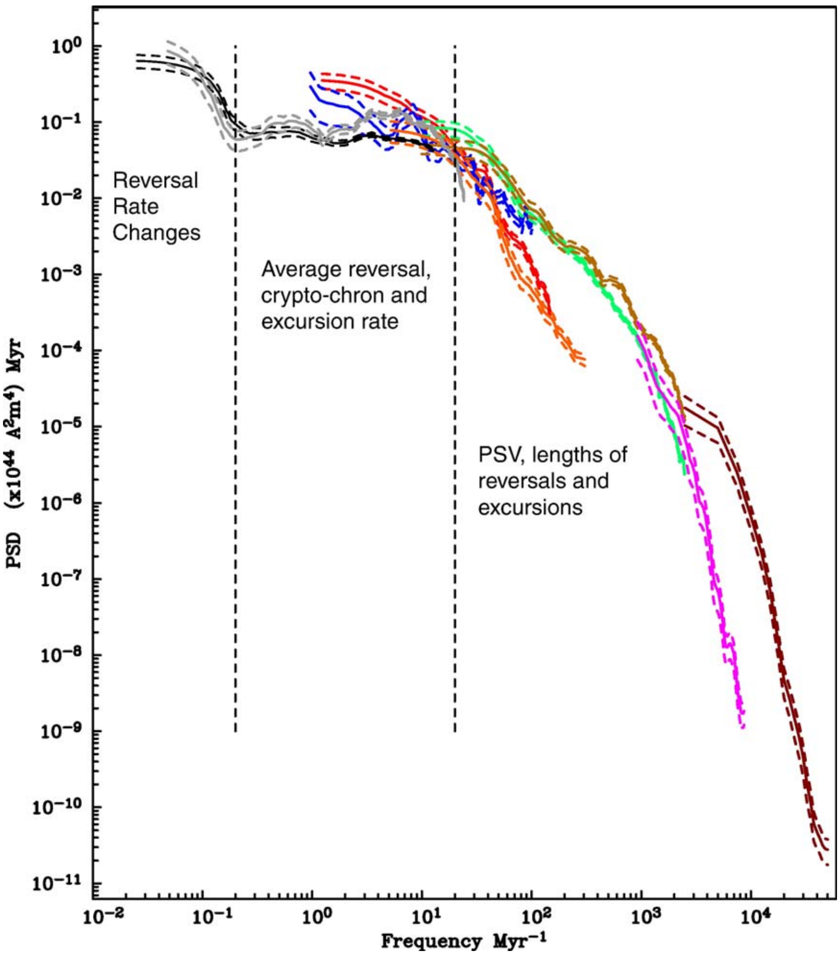

Fig. 5. Composite power spectrum of dipole moment variations: 0–160 Ma reversal record, CK95 (black), 0–83 Ma reversal record including cryptochrons, CK95cc (gray), 522 (blue), VM93 (red), 983 (green), 984 (brown), SINT800 (orange), CALS7K.2 (pink) and GUFM (dark red).

between reversals. One way to deal with more complicated field variations is to investigate the power spectrum as discussed in the next section.

5. Relative geomagnetic paleointensity and the spectrum of dipole moment variations

The SINT800 record of VADM in Fig. 2 shows a lot of structure over the Brunhes, and several of the lows in dipole moment correspond to excursional field behavior, although a tendency for these to be smoothed and attenuated by the stacking procedure used to construct SINT800 [36] means that the real dipole moment almost certainly has a somewhat larger dynamic range. Individual time series of relative paleointensity variations from sediments extend over several million years at some locations, with resolutions that vary according to local sedimentary environments, and in some cases are significantly higher than the SINT composite. A number of these have been merged with the information in the magnetostratigraphic record to construct a composite power spectrum for the dipole moment over the time interval 0–160 Ma (Fig. 5) which extends from periods involving changes in reversal rate down to the sub-centennial time scales attainable with the *GUFM* historical model. Not all the overlapping parts of the spectrum are in agreement reflecting the data sources with different levels of resolution. For example the spectrum drawn from the marine magnetostratigraphic time scales CK95 generally lies below CK95cc which includes more energy from the presence of cryptochrons. Similarly the long period 522 [37] and VM93 [27] records have energy from paleointensity variations not available in the marine magnetic anomaly record. Higher sedimentation rate records (983 and 984, [38,39]) show more structure than both lower accumulation rate records, and the heavily smoothed global average given by SINT800. CALS7K.2 lies below the

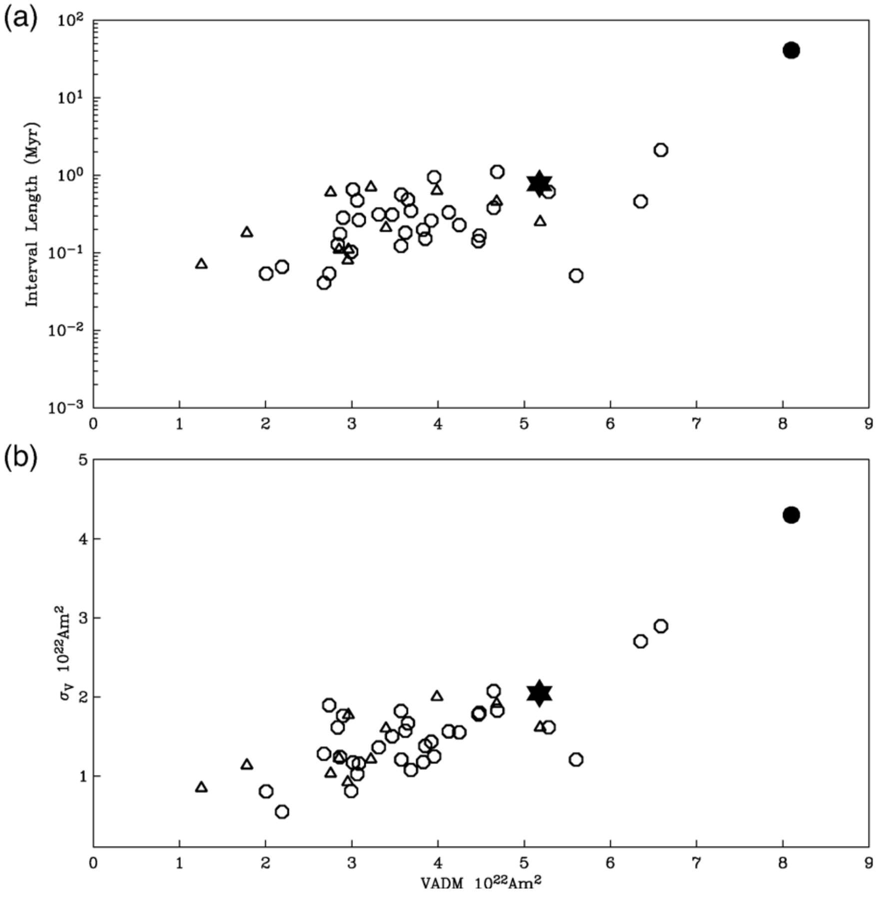

Fig. 6. (a) Dependence of polarity interval length on average VADM (upper). Open circles are from the time interval 22–35 Ma, triangles from 0–4 Ma, solid circle from the Cretaceous Normal Superchron, and star for the current Brunhes interval. (b) Field variability (measured by its standard deviation) as a function of VADM.

higher resolution GUFM. Constable and Johnson [40] suggest that in general the upper envelope will provide the best estimate of power at any given frequency.

Fig. 5 indicates the overwhelming dominance of long period changes on the geomagnetic field, highlighting the need to consider the paleomagnetic record when evaluating the likelihood of any upcoming reversal. The figure is loosely divided into three regimes, with frequency scales corresponding to (i) reversal rate changes, (ii) average reversal, cryptochron and excursion rate, and (iii) generic paleosecular variation, lengths of reversals and excursions. Only the second and third regimes are considered of primary interest here. One might hope for the power spectrum to reveal any distinction between the reversal process and excursions, but it is hard to isolate such a thing. Both CK95cc and the 522 sedimentary relative paleointensity record contain cryptochrons, and show enhanced power between 3 and 10 Myr^{-1}, but the only indication that the associated dipole moment fluctuations correspond to anything different from what is seen in the usual reversal process is the enhanced power indicating that events occur more often, and in the case of the 522 record a more focussed occurrence around 8 Myr^{-1}. There is no tangible evidence of a characteristic time scale for a reversal or excursion in part (iii) of the frequency range. The interpretation is complicated by the lack of a single long high resolution record that would allow estimation of the power spectrum across the frequency range from 1–1000 Myr^{-1}, spanning the expected time scales for both reversal and excursion rates and durations, and allowing further assessment of Lund et al.'s [20] observation that excursions tend to cluster in intervals of length 20–50 kyr. A plausible expectation might also be that records with many excursions as well as reversals would have distinct high frequency structure if Gubbins' [25] model is correct.

We have already mentioned the sawtooth appearance found in the VM93 relative geomagnetic intensity record for 0–4 Ma [27], which contributes to the high power in VM93 at long periods. Valet et al. [28] have reaffirmed this signal in a global paleointensity record for 0–2 Ma and noted the gradual (diffusive?) decay in field intensity prior to a reversal. There is no sign of this gradual decay in the recent field. In their analysis of SINT2000, Valet et al. [28] also reinforced earlier results of [37], extended by [41]) who noted a correlation between average field strength and duration of polarity intervals. Fig. 6 shows data that support this from the 522 and VM93 sedimentary paleointensity records, spanning time intervals of 22–35 Ma and 0–4 Ma respectively. Note that the Brunhes interval represented by a star in Fig. 6 is not anomalous in this context. This is probably not surprising given that when cryptochrons are considered the "reversal rate" for the 22–35 Ma 522 record is quite comparable to that for 0–4 Ma (see Fig. 3(b)). The absolute scale for the VADMs for both 522 and VM93 in Fig. 6 remains somewhat uncertain, because of uncertainties in calibrating relative paleointensity variations [42]. Recent publications [28,42] cite a global average dipole moment derived from absolute paleointensity data for the Brunhes that ranges from 5.9 to 7.5×10^{22} Am^2, but it is generally agreed to be stronger than the average for the past 160 Myr (Tauxe [43] cites 4.5×10^{22} Am^2 with a standard deviation of 1.8×10^{22} Am^2). The current dipole moment of 7.8×10^{22} Am^2 lies above the range of average values cited for the Brunhes, and is perhaps comparable to the average during the Cretaceous Normal Superchron or CNS, a polarity interval that lasted some 35–40 Myr and with an average VADM estimated at 8.1×10^{22} Am^2, but highly variable, the standard deviation is 4.3×10^{22} Am^2 [41]. Fig. 6 clearly shows that the CNS (solid circle) is anomalous, but the average for the Brunhes does not appear to be. The temporal average for VM93 for 0–4 Ma is 4.2×10^{22} Am^2, which is not very different from the 160 Ma average. Changes in the calibration would shift all data to the right in Fig. 6 (a), except the CNS value which is derived from absolute paleointensity data. However, this would not influence the basic conclusion that higher average intensity is weakly correlated with interval length.

To sum up, the current field seems strong compared to the long term average. Neither this fact nor the lack of gradual decay offers support for the idea of an imminent reversal.

6. What can be learned from recent magnetic field behavior?

The paleomagnetic evidence considered so far does not seem to favor the idea that the geomagnetic field is in imminent danger of reversing, but one cannot deny that the dipole moment is currently decreasing, and the largest changes in field strength (Fig. 1(b)) are taking place in the Atlantic hemisphere in regions that have been tied to previous reversal activity. Temporal changes in the magnetic field in Earth's core can be represented by the magnetic induction equation

$$\partial_t \boldsymbol{B} = \eta \nabla^2 \boldsymbol{B} + \nabla \times (\boldsymbol{u} \times \boldsymbol{B}).$$

Here $\eta = 1/\mu_0\sigma$ is called the magnetic diffusivity, and σ is the electrical conductivity. The first term on the right hand side represents changes due to diffusive processes, while the second contains the influence of the fluid velocity $\boldsymbol{u}$ that is needed for the dynamo process. One observation that has aroused some concern is the rate at which the dipole moment is currently decreasing, which is faster than that expected for diffusion of the magnetic field assuming that the scale length of the dipole part of the field is basically the diameter of Earth's core. It is also substantially faster than the average rate of decay cited by Valet et al. [28] for the sedimentary paleointensity record for the past 2 Myr. It seems that temporarily the contributions to secular variation from advection are acting in a way that reduces the poloidal part of the magnetic field.

Current magnetic field models like *OSVM* depicted in Fig. 1 give the highest resolution views of the geomagnetic field, but their time span is quite short. A concerted effort to gather all available historical measurements resulted in the *GUFM* field model of Jackson et al. [23], a time varying spherical harmonic representation of the geomagnetic field that has become a standard tool for studying field structure and rates of change over the past 400 yr. The limitation for reversal studies is that methods for measuring magnetic field strength (rather than just direction) have only were only developed by Gauss in 1833 Nevertheless, it has been noted that the low surface magnetic field intensity in the South Atlantic seen in Fig. 1(a) (which corresponds to a reverse flux patch at the core–mantle boundary) is a major contributor to the current dipole decay [4,5,44], that might indicate early signs of a magnetic reversal. There are ongoing attempts to understand the nature and longevity of this feature via a similar modeling effort that has been undertaken using paleomagnetic intensity and directional data from archeomagnetic artifacts, and directional data from lake and other high accumulation rate sediments [24]. This model *CALS7K.2* extends back to 5000 BC, albeit with substantially lower accuracy and resolution than for *GUFM*. Nevertheless, the model is adequate to describe large scale features like the dipole part of the magnetic field, and (as for *GUFM*) the temporal parametrization in terms of cubic splines allows an estimation of the rate of change of dipole moment for the past 7 kyr. Both the dipole moment and its temporal derivative for *CALS7K.2* are shown in Fig. 7, along with smoothed estimates of the VADMs as they would be calculated directly from the intensity observations. The differences among these estimates are discussed in some detail by [45,46], who consider that *CALS7K.2* (black line) provides the most reliable estimate, but the important point is that the general structure exhibited by all these curves is quite similar, suggesting that they provide a reasonably robust estimate of the overall dipole field behavior. Fig. 7 provides a compelling demonstration that the current rate of decay of the dipole moment is far from anomalous when placed in the context of the past 7 kyr. There are several intervals where the decay rate had been as large or larger, and it seems probable that the current decay will reverse sign during the next few hundred years as it has numerous times in the past 7 millennia.

Several additional questions related to reversals are raised by Fig. 7(b). The comparison between the paleofield model and the much higher resolution historical model for the period 1840–1990 AD clearly demonstrates that *CALS7K.2* tends to underestimate the magnitude of the temporal derivative for the dipole moment. The reason for this underestimate is that temporal resolution in *CALS7K* is no better than a few hundred years, as is clearly seen in the *GUFM* and *CALS7K.2* power spectra of Fig. 5. The black *CALS7K.2* dipole moment curve in 7(b) tracks the long period variations in $\mathrm{d}M/\mathrm{d}t$ seen in *GUFM*, but cannot resolve the sub-centennial variations. The actual magnitude of the past variations in $\mathrm{d}M/\mathrm{d}t$ is likely to be greater than in Fig. 7(b). Some paleomagnetic data from the ~15.5 Ma Miocene volcanic sequence that recorded the Steen's Mountain reversal show very rapid changes [47,48], particularly in the magnetic field directions when the intensity is low. This led some authors [49] to invoke the influence of geomagnetic storms in the external part of the field during the dipole low. It would be interesting to place an upper bound on the rate at which the dipole moment can change.

In principle, models like *CALS7K.2* can offer further insight about whether features like the South Atlantic Magnetic Anomaly are an intrinsic part of dipole decay, and likely to signal an upcoming reversal, but this is complicated by limited spatial resolution in many areas, particularly for the Southern Hemisphere. One striking feature of *CALS7K.2* is a persistent, strong reverse flux patch around 4000 BC under Africa. Although it is in the same longitudinal region as the currently discussed reverse flux patch, and occurs at a time of low dipole moment the main changes in the dipole, in particular the onset of the increase about 3600 BC, do not seem to be affected by its presence. *CALS7K.2* hardly shows really isolated patches of reverse flux at other times, probably due to the limited resolution. Bands of reverse flux stretch down from the northern hemisphere a few times in approximately the same regions, which are Africa, South America and towards Western Australia. Such bands cannot be uniquely associated with times of either low or decreasing dipole moment, and should in any

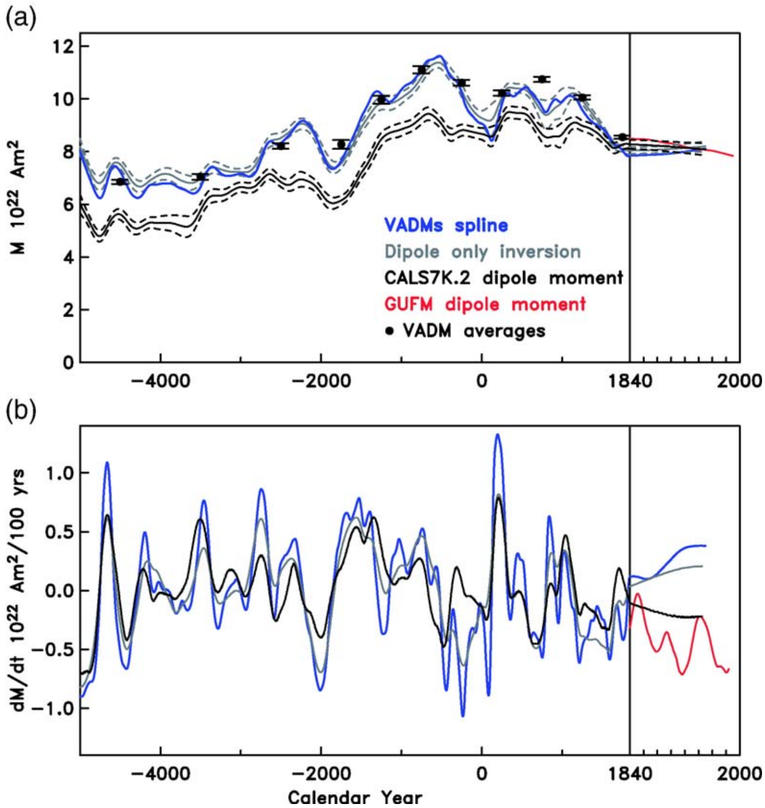

Fig. 7. (a) Dipole moment estimates (M) and (b) their rates of change for the past 7000 yr obtained from the same data by different methods: 500 or 100 yr average VADMs (black dots) and weighted spline fit (blue line) to individual VADMs, spherical harmonic inversion of intensity and directional data for a dipole only (gray line), dipole moment estimate from CALS7K.2 (black line) and in the expanded right part also from the historical model GUFM (red, [23]). Dashed lines give 1 standard error for the spherical harmonic results as reported using the bootstrap technique described in [46].

case be viewed with some caution: *CALS7K.2* almost exclusively uses data over the continents but not the oceans, one must be wary of complex interpretations in regions that rely on small numbers of records and sparse data distributions.

Where does the energy in the dipole go when the field decays? This question cannot be addressed by surface field observations alone: the poloidal part of the field which escapes from the core is measurable at Earth's surface, but the toroidal part of the field is confined to Earth's core and cannot be measured directly, although it must play an important role in the dynamic processes that contribute to a self-sustaining and reversible dynamo [50,51]. The available options for dipole energy loss would appear to be dissipation as heat, transformation into kinetic energy, and/or transformation into toroidal or higher degree poloidal fields. Korte and Constable [24] see evidence in *CALS7K.2* for increase in power at higher degrees when the dipole is reduced at some times (but not always), and Valet et al. [28] attribute the gradual decay in dipole moment in the *SINT2000* record before reversal to diffusion effects. The low sedimentation rates in *SINT2000* compared with *CALS7K.2* could also easily mask similar kinds of rapid field changes in the decay phase, and perhaps some shorter term variations as the poloidal field is re-energized after the transition. Kinematic dynamo models have often focussed on the question of how the field will grow and sustain a dynamo, providing the energy needed to overcome diffusion. Livermore and Jackson [52] show that axisymmetric flows of the type considered representative of those generating the main energy source for the geodynamo can preferentially excite transiently generated fields that are predominantly axisymmetric, but it is unclear why one should expect the temporal asymmetry about reversals seen in the SINT2000 intensity record.

Detailed studies of reversals in several numerical dynamo simulations suggest that a range of different physical processes in the core can be involved (e.g. [12,53,54]). In a recent study of the reversal mechanism in a dynamo driven by compositional convection Wicht and Olson [55] found that regular reversals can be generated primarily by magnetic induction effects, and are not triggered by changes in the fluid flow. Material rising inside the tangent cylinder plays an important role in producing reversed magnetic field. The surface expression of these reversals is short in duration compared with the whole process, and entails rapid growth and poleward motion of reversed flux spots which provides an efficient mechanism for changing the field polarity. This dynamical process is also important (but less regular) in reversals studied by Sarson and Jones [56] who attributed them to fluctuations in the strength of a polar upwelling plume. In contrast Takahashi et al. [57] found reversals originating deep in the core at low latitudes, growing toward the core surface, and subsequently spreading from low to high latitudes. None of their reversals or excursions originated inside the tangent cylinder, although the surface manifestations included poleward movement of broad flux lobes like those seen at high latitudes in Fig. 1(a) before or at the beginning of a transitional period.

Numerical models span a range of control parameters and boundary conditions (e.g. [51,58]) and demonstrate more similarity to the geomagnetic field than one might perhaps reasonably expect, given how far they lie from the correct parameter regime for the earth. Hollerbach [59] explains the enormous range of time scales associated with the geodynamo problem, and the difficulties in approaching the correct parameter regime. Parameters in current use lead to viscous boundary layers that are much thicker than expected for Earth's core, preventing the study of thin boundary layers and rapid dynamics associated with them. Studies in a more appropriate parameter regime are inhibited by the need for both better spatial resolution, and shorter time steps in the simulations, although a recent simulation by Takahashi et al. [57] appears to operate in a dynamic regime very close to that expected for the Earth, where the effect of viscosity plays a negligibly small role in core dynamics. These and other concerted efforts to explore the effects of systematically varying control parameters will allow modelers to assess the effects of the numerical limitations and determine whether simulations can be used to make useful inferences about the geomagnetic field or will inevitably all provide the same kind of generic agreement with paleofield observations.

7. Summary and discussion

Paleomagnetic considerations offer little support for the idea that the geomagnetic field is currently entering a reversal. When the field is modeled as a Poisson process with a monotonically varying rate, 95% confidence bounds on the reversal rate are (2.5, 29.1) reversals per million years. The lower bound predicts polarity intervals as long or longer than the current one about 14% of the time (Table 1). The upper bound gives very low probabilities, but suggests a reversal rate so high (30 Myr^{-1}) that reversals could not be regarded as independent events, invalidating the Poisson process as a plausible statistical model for occurrence of reversals. More realistic estimates must take long term variations of paleointensity into consideration. The power spectrum of paleointensity variations has most energy at long periods, and durations of polarity epochs are correlated with average paleointensity of the interval. The current dipole moment is slightly less than twice the average for 0–160 Ma. Statistical models of paleosecular variation [60,61] estimate the standard deviation in the axial part of the dipole at about 35–40% of its mean value in agreement with long term paleomagnetic observations. Currently the VADM remains 2–3 standard deviations greater than the mean. The present rate of change does not appear to be anomalous when compared with values for the past 7 kyr. Some paleomagnetic observations of intensity variations have been used to argue that the field decays at a more gradual rate than during its increasing phase immediately following a reversal. There is no evidence suggesting that such a gradual decay is taking place at present. Collectively these observations suggest that the interpretation of the current dipole decrease as the beginning of a reversal [4,5] is unwarranted. However, there remains an open question of how one might (at a time of lower dipole moment) determine that the magnetic field is irrevocably committed to a reversal.

In the future we can expect that time varying field and secular variation models will continue to be developed, providing improved estimates of rates of change for the magnetic field on all time scales. We can expect a crude million year magnetic field model, but it is unlikely that the resolution will be better than several hundreds of years for any data older than 10 ka, and it will be much lower for the vast majority of the current Brunhes normal polarity interval.

Before we abandon the Poisson or other renewal process as a statistical model capable of providing useful insight, it is worth noting that in principle numerical dynamo simulations can provide us with a mechanism for studying the usefulness of this kind of description for the reversal process. Although it remains a challenge to determine which parts of these simulations accurately reflect the kind of processes going on in Earth's core, they do demonstrate several kinds of Earth-like behavior. It is perhaps possible that these models essentially see through the overly thick boundary layer to generic field structures that lie below, and that correct treatment of the boundary layers may not be critical to some longer term aspects of dynamo behavior. Support for this view is offered by observations that properties like the rms field strength scale independently of the parameters controlling diffusion (e.g. [62,63]).

Detailed paleomagnetic observations will continue to contribute to our views about excursions and reversals (e.g. [22]). Resolution in dating transitional directions and intensity variations is improving, and it should be possible to acquire better estimates of rates of change in magnetic field strength for reversals and excursions. This may make it possible to test whether there are systematic differences between the two, perhaps lending support to the idea that excursions are accidental occurrences of deviant directions arising from secular variations during sustained periods of low dipole moment. Improved temporal and spatial resolution in paleosecular field modeling on long time scales may ultimately make it possible to test whether specific kinds of symmetries in the field are present during excursions and reversals. However, the paleomagnetic observations are limited by the recording medium, and we cannot expect that on their own they will provide the kind of detailed picture necessary to understand what occurs in the core during a reversal. Numerical studies of the geodynamo now routinely produce reversals (e.g. [11,54,64,65]). It is understood that reversals require high Rayleigh number regimes [54]. Detailed analyses of simulated reversals are possible, particular flow regimes can be identified (e.g. [55]), and further reconciliation (in a statistical sense) of these results with paleomagnetic observations must be an essential contribution to understanding the physical processes that lead to geomagnetic field reversals.

Absence of evidence for an imminent reversal should not lead to complacency. We cannot predict the long term changes in Earth's core, but it is inevitable that the field will continue to exhibit secular variation on all time scales and the current dipole moment will continue to change. The record for the past 7 kyr shows variations by about a factor of two and these are large enough to have significant consequences. If the dipole moment drops to 50% of its current value one can expect a corresponding decrease in the radius of the magnetosphere, whose size is controlled to first order by a balance between static pressure generated by the geomagnetic field and the dynamic pressure of the solar wind (Fig. 8). The anticipated scaling is radius proportional to the cube root of dipole moment [66]. One should expect such changes to influence cosmic ray activity in the upper atmosphere as well as the nature and impact of geomagnetic storms. The effect of increased radiation dosage due to enhanced cosmic ray activity on the evolutionary development of individual species is generally taken to be negligible (see [67]), but the influence of space weather is less clear.

The physical causes of space weather variations are modulation in galactic cosmic ray activity, solar

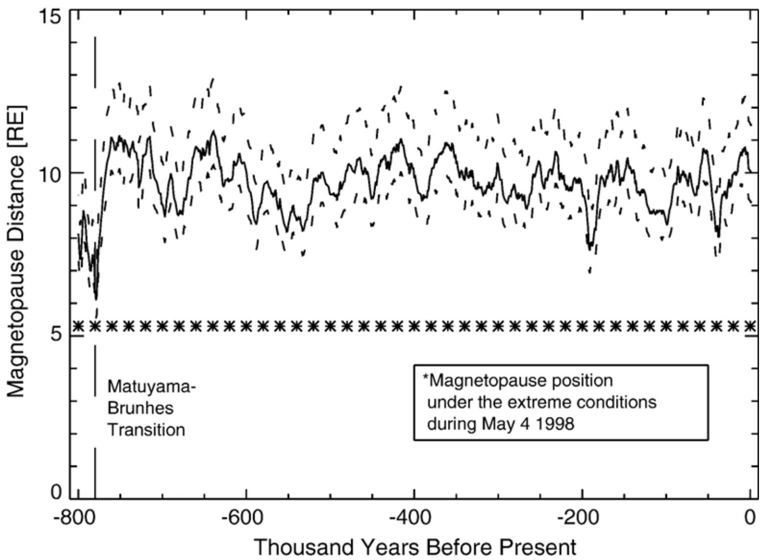

Fig. 8. Estimated radius of the magnetosphere for the past 800 kyr derived from the SINT 800 record of Fig. 2, using [66] scaling relation. Dotted lines are error bars indicating the variability anticipated from changes in dynamic pressure of the solar wind (after [75]).

energetic particles, and geomagnetic storms. Periods of enhanced solar activity can generate solar flares and coronal mass ejections, which send energetic solar particles into the heliosphere and magnetosphere. These travel ahead of the bulk of the solar wind and result in charged particle precipitation events in Earth's polar cap regions. The polar cap (of about 30°) is specified as the region in which magnetic field lines are open, for which the poleward boundary of auroral emissions is an often-used proxy. The subsequent geomagnetic storms are manifest as enhanced magnetospheric and auroral activity, and can be damaging to technological infrastructure [68,69]. Increased particle precipitation in the form of solar proton events from coronal mass ejections has been linked to changes in atmospheric composition [70], and experiments with a two dimensional photolysis and transport model for the atmosphere suggest that expected ozone losses during a magnetic reversal could result in significant changes in UV radiation accompanied by changes in stratospheric temperature and circulation and thus may have implications for global climate change [71]. Enhanced cosmic ray activity in the upper atmosphere has also been linked to cloud formation processes [72,73], provoking debate about whether variations in cosmic ray activity or solar irradiance [74] generate the most important influences on climate change.

It remains unclear what the exact role of the geomagnetic field is in influencing space climate, the very long term variations in space weather. Siscoe and Chen [66] proposed scaling relations for how the external ring current variations and width of the polar cap vary with dipole moment and went on to infer that the size and frequency of magnetic storms would increase with decreasing M. Ultré-Guérard and Achache [49] supported this view in their analysis of the Steen's Mountain reversal record. In contrast Glassmeier et al. [75] use the volume rather than cross section of the magnetosphere to infer that fewer particles would be trapped in the radiation belts, and the strength of the external ring current typically represented by the Dst index would decrease with decreasing dipole magnetic moment. Their results suggest that ring current magnetic effects are of minor importance during polarity transitions. Glassmeier et al. also discuss new scaling analyses for the ionospheric fields which influence the size of the polar cap, and conclude that the dipole moment variations would have a much larger influence on these. The ionosphere is expected to grow in size relative to the magnetosphere as the dipole decreases, and could perhaps generate a magnetosphere that is much more strongly influenced by rotation than the one we see today.

Overall the scaling results derived from simulation of the paleomagnetosphere suggest that the secular change in geomagnetic dipole moment plays a smaller role than the solar wind in large scale magnetospheric variations. However, the arguments used must be viewed with some caution, since they do not take account the increased geomagnetic field complexity that could occur with low dipole moments, and the physical models may need modification as the various parts of the system interact in unexpected ways. Improved understanding of these areas is needed in investigating the influence of long term geomagnetic field variations and associated changes in the magnetosphere on cosmogenic nuclide production. The influence of solar variability on cosmogenic isotope production plays an important role in paleoclimate studies that can only be properly assessed when the magnitude of changes in magnetic field strength are better documented.

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