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Eastward and westward drift of the Earth's magnetic field for the last three millennia

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Abstract

We analyse the secular variation captured by the archaeomagnetic field model CALS7K.2 in an effort to determine episodes of eastward and westward motions of Earth's magnetic field at the core–mantle boundary (CMB) over the past 3000 yr. The direction, amplitude and geographical distribution of these motions are described. We find that the clearest azimuthal motions are observed at mid- to high latitudes in the Northern hemisphere, where both eastward and westward motions occur. These azimuthal motions correspond to displacements and distortions of the two main, quasi-stationary, high-latitude magnetic flux patches. Similar motions are not observed in the Southern hemisphere, although this may be a consequence of the poorer data coverage there. The globally averaged drift for the past 1000 yr has been westward since 1400 AD, but eastward between 1000 AD and 1400 AD. In the broad region of the CMB under Europe, the times of transition in the direction of the mean azimuthal motion coincide with the times at which "archaeomagnetic jerks" have been reported. Our results suggest that these are caused by a relatively rapid (<100 yr) change in the direction of the underlying azimuthal flow near the core surface. We find indications that equatorial westward motions of field features at the CMB, similar to those observed during historical times, may have been present for much of the past 3000 yr. When observed, these low-latitude motions are most prominent in the Atlantic hemisphere, which we interpret as a signature of core–mantle thermal coupling.

Keywords: geomagnetism; archaeomagnetism; secular variation; eastward and westward drift; geodynamo; core–mantle coupling

1. Introduction

The Earth's magnetic field is believed to be maintained by convective motion in its metallic liquid core, a process known as the geodynamo. Although many advances have been made in recent years, our knowledge of the details involved in this process remains poor. This is in part because our observations of the magnetic field inside the core are very limited: only the radial part of the field near the surface of the core is directly accessible, and of that part, only the largest spatial features can be observed. In addition, observations with a spatial and temporal coverage sufficient to extract aspects of the dynamics cover only a small fraction of the temporal spectrum of the geodynamo variations. Nevertheless, the observed time-

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changes of the field, also referred to as secular variation, may be used to gain insight into the processes that are responsible for maintaining the field. As such, the secular variation remains the best window into the dynamics taking place inside the core.

Of the various aspects of the secular variation, the westward drift observed at the Earth's surface is arguably the most well-known and documented feature. The earliest observation dates back to more than three centuries ago, when Edmund Halley [1,2] identified specific features of the field that could be traced moving westward. Almost two hundred years later, Bauer [3] and Carlheim-Gyllensköld [4] showed that the westward drift had persisted and had been a feature of the secular variation since the mid-16th century. As the quality of the observations improved during the last century, it allowed a more accurate quantification of the westward drift. Using the magnetic field maps of Vestine et al. [5] which were built from observations of the field between 1905 and 1945, Bullard et al. [6] concluded that the drift of the non-dipole part of the field averaged over the entire planet for the period 1907–1945 was $0.18° \mathrm{yr}^{-1}$. In the two decades that followed, several studies found a general agreement with this result [7–11]. The global westward drift of the Earth's magnetic field was therefore a well established feature of the secular variation, even though it was recognised that its spatial variations were important and that its rate was not constant.

This perspective was altered by the advent of time-dependent models of the magnetic field directly at the core–mantle boundary (CMB) obtained by regularised inversion (e.g. [12–14], and references therein). The secular variation that emerges from these models shows that the azimuthal motions that give rise to the westward drift are observed most clearly in the equatorial region of the Atlantic hemisphere, while under the Pacific ocean azimuthal motions are less prominent. This picture of field evolution at the CMB was recently described in detail by Finlay and Jackson [15], who used a technique designed to highlight azimuthally moving field features. The current view is thus that the westward drift is the surface expression of the movement of localised field features at the CMB, and is not a global phenomenon.

It is, however, unclear whether this pattern of westward motions of field features in the Atlantic hemisphere at the CMB is a persistent feature of the geodynamo or whether different patterns of azimuthal motions have occurred in the past. Early analyses of archaeomagnetic data suggested that the surface westward drift had been a feature of the secular variation for at least the past 700 years [16,17]. Other studies argue that the westward drift has persisted for much longer (e.g. [18]). On the other hand, evidence of a dominant eastward motion under Europe roughly between 900 AD and 1350 AD has been reported [19–21]. Moreover, simple azimuthal core flows spanning the past 3 millennia indicate that the globally-averaged drift at the CMB may have been sometimes eastward and at other times westward [22].

Establishing the pattern of secular variation over millennial timescales is important because it provides direct information on the geodynamo over the timescale of convective motions in the core. This may then provide better guidance to test numerical simulations of the geodynamo. It may also help resolve some of the questions concerning the present-day secular variation. For instance, what proportions of the historical westward motions are due to advection by a westward flow [6] and phase propagation of hydromagnetic waves [23,24]? Also of interest is whether the current geographical distribution of secular variation is purely a consequence of the inherent spatial variations of the geodynamo [25] or partly due to coupling with the lower mantle [26,27].

In this paper, we revisit the question of the westward drift by investigating the pattern of azimuthal motions of magnetic field features at the CMB over the past three millennia. The quantity and quality of the available archaeomagnetic and lake sediment data has increased considerably in the last few years [28]. Time-dependent models of the magnetic field built upon these data remain crude [29–32], but now permit a much better temporal and spatial characterisation of the secular variation than that inferred in earlier studies. We use the archaeomagnetic field model CALS7K.2 [32], which covers the time interval between 5000 BC and 1950 AD. We limit our investigation to the last 3000 yr of the model for which our analysis yields most definitive results.

It has to be emphasised that CALS7K.2 is a heavily-regularised field model constructed from data with large measurement and dating uncertainties that are rather sparsely and unevenly distributed in space and time. We fully recognise that the limitations of this field model may severely affect our conclusions concerning the nature of azimuthal secular variation. Nevertheless, we regard CALS7K.2 as the best approximation yet published to the true global field evolution over the past few millennia. We argue that it is therefore of value to analyse and characterise the patterns of azimuthal secular variation it contains. The picture of azimuthal secular variation presented here will undoubtedly be refined and improved upon in the future as new datasets and better models become available.

2. Time–longitude plots of field evolution

The secular variation captured by CALS7K.2 takes many forms. Individual magnetic field features are seen to be growing and/or decaying, and motions of features are observed in both azimuthal and meridional directions. In the present study, our attention is entirely focused on azimuthal motions. To isolate this part of the secular variation, we process CALS7K.2 in the following way. We first remove a time-averaged axisymmetric component. This is because azimuthal motions can only be observed in the non-axisymmetric part of the field. The remaining part of the field is then high-pass filtered to remove quasi-stationary, non-axisymmetric, features. The model that remains captures primarily the evolution of non-axisymmetric field features and is therefore very good for imaging azimuthal motions. To avoid confusion with the original model, we shall refer to this processed magnetic field model as CALS7K.2p. The results presented here have been obtained using a high-pass filter threshold of 2000 yr, which was found to be the optimal choice; with a lower threshold too large a part of the original model is eliminated, while with a higher threshold quasi-stationary features obscure the secular variation. More information on the methodology and on the details of the filtering process can be found in Finlay [33] and Finlay and Jackson [15], and will also be the subject of a future publication.

Coherent azimuthal displacements of magnetic field features at a given latitude are best visualised in time–longitude (TL) plots. In Fig. 1, we present TL plots of the radial part of the magnetic field at the CMB from CALS7K.2p at several latitudes for the time interval between 1000 BC and 1700 AD. Red contours indicate radially outward magnetic field, and blue contours radially inward. In these plots, westward motions appear as continuous bands of either red or blue, angled diagonally in the general orientation of bottom right to top left. Conversely, diagonal bands oriented from bottom left to top right are indicative of eastward motions. The speed of azimuthal motion can be determined from the angle of the diagonal band: a shallower angle corresponds to a faster motion. Similar plots can be constructed for the horizontal field, however, they do not provide additional information since all field components are derived from the same potential.

For comparison, we include in Fig. 1h a TL plot showing the azimuthal motions at the equator during historical times. This plot is similar to one presented in Finlay and Jackson [15], and displays the radial field from a processed version of *gufm1* [14] obtained by removing its time-averaged axisymmetric part and applying a high-pass filter with a threshold of 400 yr. Strong and persistent westward motions are clearly observed in the Atlantic hemisphere (centred on 0° E longitude) at a rate of 0.27° yr^{-1}, corresponding to an azimuthal speed of 17 km yr^{-1}. These coherent azimuthal motions observed in the last 400 yr give rise to the westward drift.

In CALS7K.2p, coherent azimuthal motions are found most noticeably at Northern latitudes. At 60° N (Fig. 1a), westward motions are present in the hemisphere centred on 120° E between 1000 BC to 500 AD. Equally visible are eastward motions in the opposite hemisphere (centred on 60° W) between 700 AD until 1500 AD. The boundaries of these regions are not sharp: at European longitudes for instance (near 0° E), both eastward and westward motions occur. This general description at 60° N also applies at 40° N (Fig. 1b). An eyeball estimate of the typical eastward and westward rates of motion at 40° N gives 0.15° yr^{-1}, or 8 km yr^{-1}.

At 20° N (Fig. 1c), the equator (Fig. 1d) and 20° S (Fig. 1e), persistent westward motions in the hemisphere defined between 60° W and 120° E are observed for most of the time interval studied, even though the connectivity of some the features is not very good. No clear evidence of azimuthal motion in either direction is observed in the opposite hemisphere. This is geometrically consistent with the historical equatorial westward motions. An eyeball estimate gives a drift rate ranging between 0.1 and 0.2° yr^{-1}, a weaker rate than that observed over historical times, though this could be a consequence of the limited resolution of CALS7K.2.

Finally, at 40° S (Fig. 1f) and 60° S (Fig. 1g), no strong evidence of azimuthal motion is found. This is partly a consequence of the poorer data coverage of the Southern hemisphere. In a sense, this is reassuring: if similar motions to those observed at 40° N and 60° N had been present despite the much poorer data coverage, the recovered motions at all latitudes may have been viewed with suspicion.

3. Dominant azimuthal velocities

The TL plots of Fig. 1 provide visual evidence for the patterns of azimuthal motions of field features at the CMB. In order to quantitatively analyse the predominant azimuthal motions at each latitude, and to determine their speed, we use a technique based on the Radon transform [34]. The Radon transform of the two-dimensional image of a TL plot gives a measure of

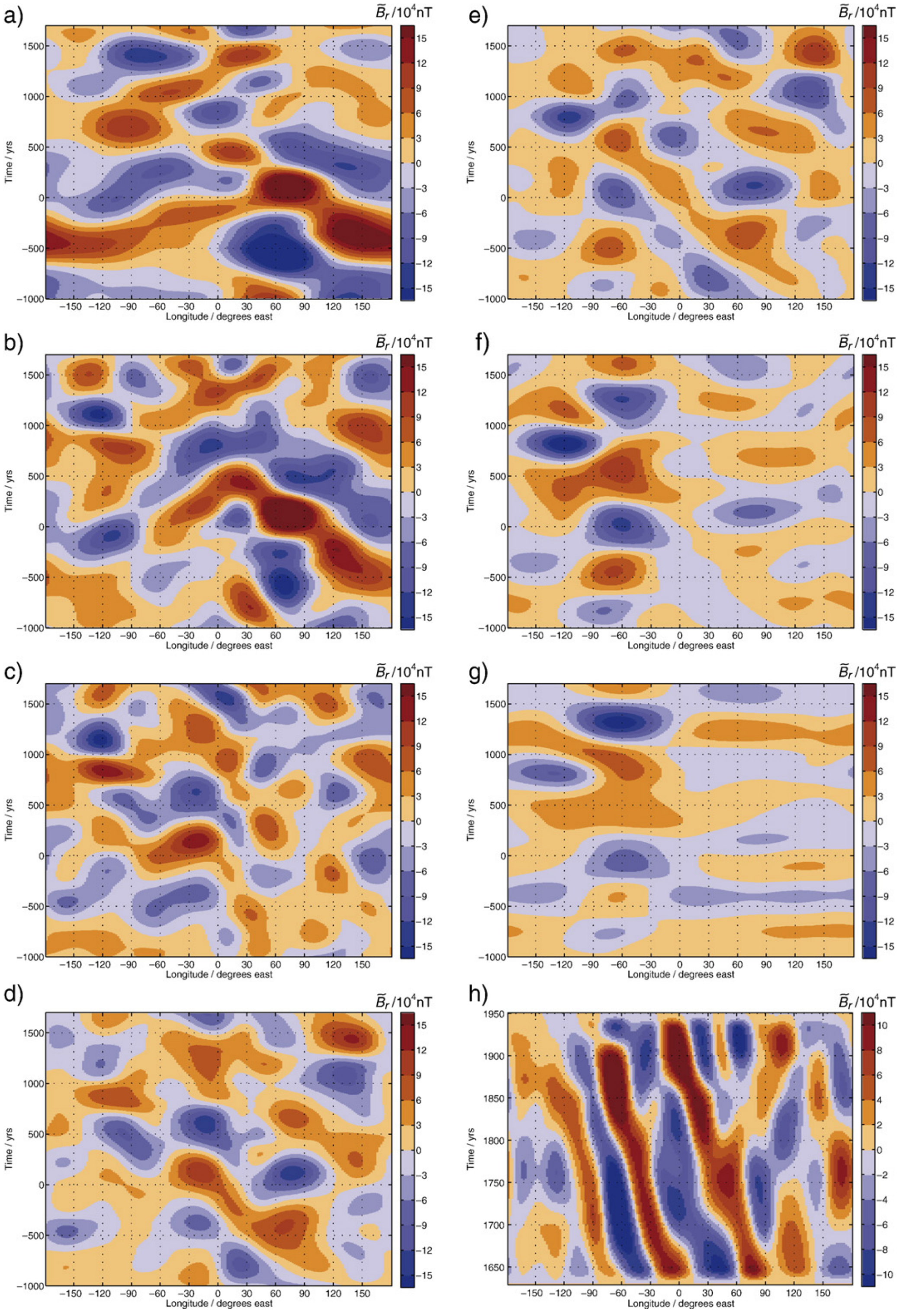

Fig. 1. Time–longitude (TL) plots of the radial part of the processed field model CALS7K.2p at the CMB at a) 60° N, b) 40° N, c) 20° N, d) equator, e) 20° S, f) 40° S, g) 60° S. h) TL plot of the radial part of *gufm1* (after processing) at the equator of the CMB (from Finlay and Jackson [15]). Details concerning the different choices of filter threshold used in the analysis of the archaeomagnetic and historical field models can be found in the text.

the amount of the signal coherently travelling at a given azimuthal speed. It allows us to objectively find the dominant azimuthal motions. This method has been developed and presented by Finlay and Jackson [15] and Finlay [33], and previously applied to identify the dominant azimuthal motions over the last 400 yr in the historical field model *gufm1* [14]. Preliminary results of the application of this technique to archaeomagnetic field models were first reported by Finlay [33].

By applying this procedure to all latitudes we obtain, for a specified time-interval, a plot of the power as a function of azimuthal speed and latitude. We refer to such latitude–azimuthal speed power plots as LASP plots. In Fig. 2a, b and c, we show LASP plots of CALS7K.2 obtained for time-windows of 400 yr centred on 1750 AD, 1000 AD and 0 AD, respectively. Removal of the time-averaged axisymmetric field and high pass filtering with a 2000 yr period threshold was

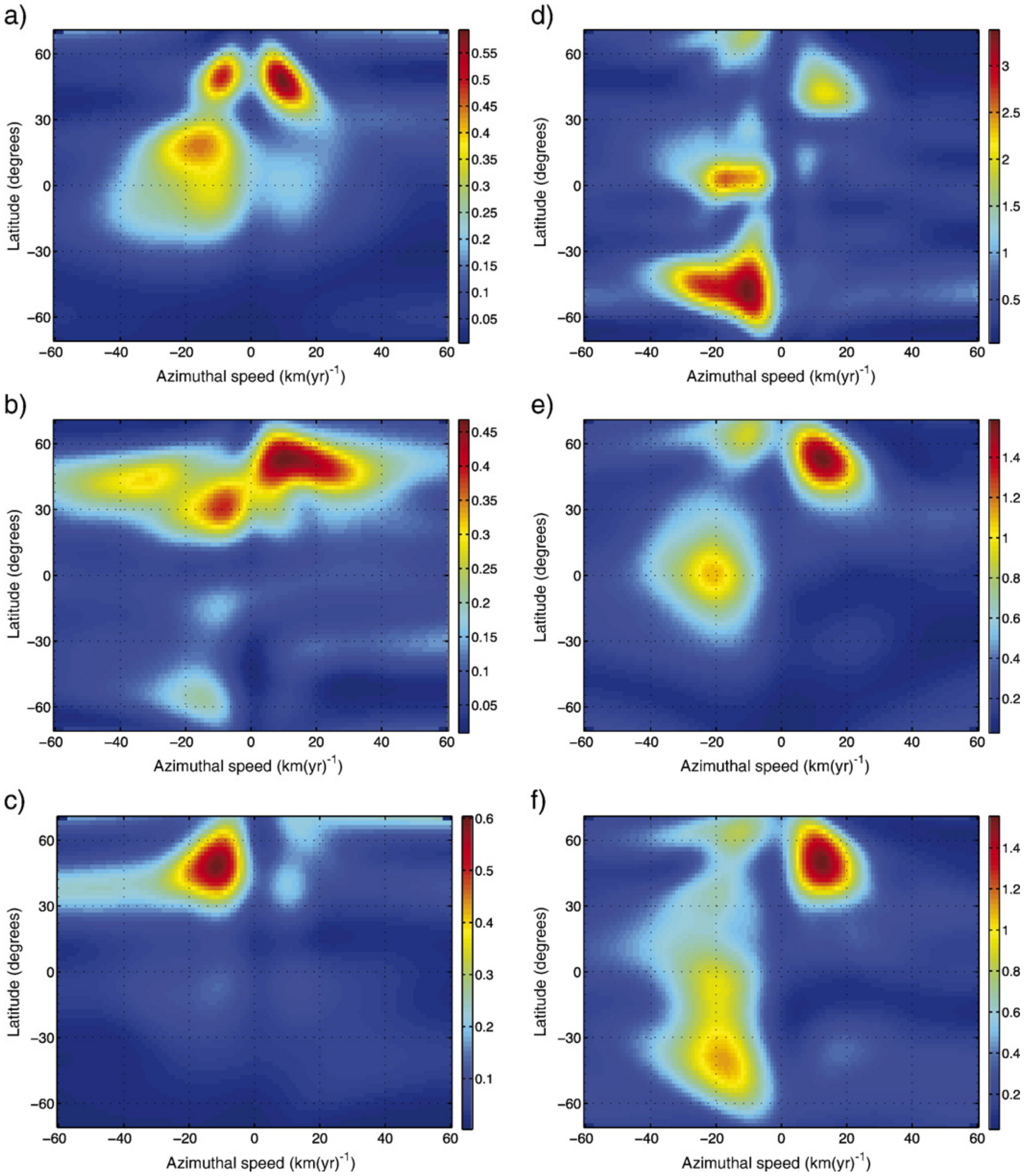

Fig. 2. Latitude–azimuthal speed power (LASP) plots of CALS7K.2 for 400 year time-windows spanning a) 1550–1950 AD, b) 800–1200 AD, c) 200 BC–200 AD. d) LASP plot of *gufm1* (1590–1990 AD) with the same processing as applied to the archaeomagnetic field model. LASP plots of synthetic field models based on evaluating *gufm1* at archaeomagnetic data locations and time spanning e) 1590–1990 AD and f) 800–1200 AD. Colour scales are in units of 10^{16} nT^2. All azimuthal speeds are defined at the CMB.

carried out on each 400 yr window separately. We note that the order of filtering and windowing and the precise choice of filter threshold can influence the results obtained, as was previously discussed by Finlay [33]. The clearest signals are observed at mid- to high latitudes in the Northern hemisphere. For the time-windows centred on 1750 AD (Fig. 2a) and 1000 AD (Fig. 2b), an eastward motion of approximately 10 km yr^{-1} near 45° N is the dominant signal. The dominant signal at 0 AD (Fig. 2c) is also approximately 10 km yr^{-1} at 45° N, but it is now westward. These signals correspond to the mid- to high-latitude azimuthal motions observed in Fig. 1a and b. In each of Fig. 2a–c, significant power is also present in the reverse direction at the same latitude; this is because azimuthal motions in the opposite direction do occur simultaneously in different longitudinal regions as observed in Fig. 1a and 1b. In agreement with Fig. 1, we do not find strong evidence of similar motions in the Southern hemisphere. In the few instances when a signal is observed, such as at 50° S in Fig. 2b, its power is always much smaller than the Northern hemisphere signals. It is difficult to identify convincingly an equatorial westward signal in our LASP plots corresponding to the features seen in Fig. 1c–e, primarily because their amplitude is weak compared to the higher latitude signals. When an equatorial signal is present, either its power is rather weak, as in Fig. 2b and c, or it is smeared over a broad range of latitudes and speed, as in Fig. 2a.

For comparison with azimuthal motions determined from historical field models over the past 400 yr, we show in Fig. 2d a LASP plot for *gufm1* which has been processed in the same manner as Fig. 2a–c. Three distinct signals are observed: the equatorial westward motion with maximum power at 17 km yr^{-1}, an eastward motion centred near 45° N, and a westward moving feature centred near 45° S. The presence of distinct signals at mid-latitudes in this historical model shows that the mid-latitude azimuthal motions we identified in CALS7K.2 are not atypical — they have also clearly been present during the past four centuries. The signal at 45° S is associated with the appearance of a reverse flux patch near the southern tip of Africa and its subsequent westward displacement. Similarly, the eastward signal at 45° N appears to be related to the motion of the Siberian high-latitude flux concentration after 1800 AD. We note that these signals were also found in the study of Finlay and Jackson [15] but with weaker power (see their Fig. 3). This is because they used a high pass filter threshold of 400 yr; by allowing signals with periods of up to 2000 yr to be recovered, the mid-latitude azimuthal motions become as prominent as the equatorial westward motions.

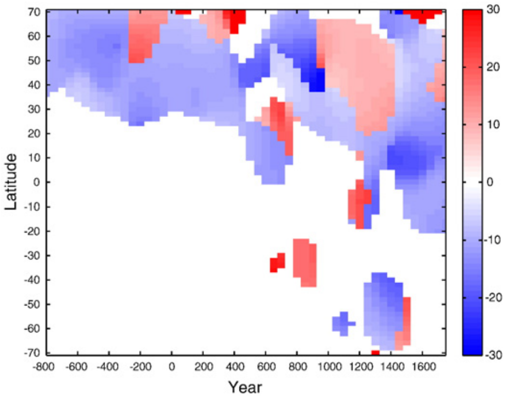

Fig. 3. Azimuthal speed associated with the largest power at each latitude as a function of time in LASP plots. Positive speeds (red) correspond to eastward motion and negative speeds (blue) to westward motion. White regions represent either zero drift, or regions where the power is below the selected cutoff value (see text). Speeds are at the CMB and are in units of km yr^{-1}.

The comparison between Fig. 2a and d gives an indication of the ability of CALS7K.2 to recover azimuthal motions, since the time-window of Fig. 2a overlaps with *gufm1* for 360 yr. The eastward signal at 45° N is well captured in Fig. 2a. The westward signal at 45° S is not present in Fig. 2a because there are no archaeomagnetic data in the Southern hemisphere after 1850 AD, and CALS7K.2 misses the appearance and motion of the African reverse flux patch. The equatorial westward motion is captured in Fig. 2a, though its peak of power is smeared and displaced in both latitude and azimuthal speed. This is likely a reflection of how data errors, heavy regularisation and a lack of Southern hemisphere data in CALS7K.2 prevent a precise retrieval of azimuthal motions at low latitudes.

Fig. 2e and f show the results of a synthetic test we carried out to assess the influence on LASP plots of the non-ideal spatial and temporal distribution of data used to construct CALS7K.2. We considered two 400 yr windows: 1590–1990 AD (Fig. 2e) and 800–1200 AD (Fig. 2f). For each interval we constructed a synthetic dataset by evaluating *gufm1* at the times (mapping the start of each time window to 1590) and locations of the CALS7K.2 dataset [28]. We used these synthetic datasets to construct two regularised, time-dependent, field models using the same number of spherical harmonics, same spline spacing and same regularisation as CALS7K.2. LASP plots (Fig. 2e and f) were then produced in the same manner as were Fig. 2a–d. Fig. 2e,f are thus based on the same field evolution and have undergone the same processing as Fig. 2d. Differences between Fig. 2e,f and the 'synthetic truth' of Fig. 2d can only result from differences in the spatial and temporal data distributions used to sample the field evolution and illustrate the effect that the sparse data distributions used to derive CALS7K.2 may have on the LASP plots of Fig. 2a–c.

In both Fig. 2e and f, as well as in other time-intervals spanning the past 3000 yr that we have tested, the eastward azimuthal motion at 45° N and the westward signal at 65° N are similar to that found in the control case of Fig. 2d. This indicates that the data coverage in CALS7K.2 over the past 3000 yr is sufficient to capture the Northern hemisphere mid-latitude azimuthal motions that are the major findings of this study. The westward signal in the Southern hemisphere in Fig. 2d is absent in Fig. 2e because of the lack of data in that region from 1590–1990 AD, while it is approximately imaged in Fig. 2f because the data coverage from 800–1200AD in the Southern hemisphere is better. The recovery of this signal in other time-intervals is never better than in Fig. 2f and our confidence in azimuthal motions in the Southern hemisphere is low. The equatorial motion is approximately recovered in Fig. 2e,f and in other time windows we tested but the power is smeared over a larger range of speed and latitudes than in Fig. 2d. It should be borne in mind that these synthetic tests investigate only the limitations introduced by the CALS7K.2 data distribution and do not take into account the effect of errors in these data. Considering the differences in the resolution of the equatorial motion between Fig. 2d,e and a, it seems that data errors are a major factor causing the smearing and displacement of the underlying signal. This suggests that although we might be able to diagnose the presence of an equatorial azimuthal motion process, its speed may not be accurately determined due to the limitations (especially those associated with data errors) of CALS7K.2. It is beyond the scope of this letter to discuss in detail the limitations of the secular variation captured by CALS7K.2. We note, however, that the tests we have performed suggest the direction of azimuthal secular variation in CALS7K.2 is reliable and that the model has best resolution at Northern mid-latitudes where we have identified motions of interest.

In Fig. 3 we present the temporal variations in azimuthal field motions captured by CALS7K.2 over the past 3000 yr. It was produced from LASP plots spanning 400 yr windows at 50 yr intervals with central time moving between 800 BC and 1750 AD. For each of these LASP plots we determined the dominant azimuthal velocity at each latitude by recording the value at which the power is maximum. This allows a global representation of how the dominant azimuthal motion at each latitude has varied as a function of time. To focus on the moving features that are most robust, we have retained only the azimuthal motions for which the maximum power on the LASP plot was above a specified cutoff value. We have chosen this cutoff value to be the average power in a LASP plot multiplied by a constant $p_c = 0.9$. Thus, white regions on Fig. 3 represent either zero azimuthal motions, or regions where there is no clear signal and the power is below this cutoff value. Our choice $p_c = 0.9$ is somewhat arbitrary, but was selected after trials with a range of p_c values because it provided a map which removed the more dubious signals (especially in the Southern hemisphere) while retaining signatures of azimuthal motions associated with lower amplitude magnetic field features.

The results in Fig. 3 illustrate once more that both eastward and westward motions are observed over the last 3 millennia. More specifically, at mid- to high latitudes in the Northern hemisphere westward motions dominate from 800 BC to 900 AD and between 1400 AD and 1650 AD, while between 900 AD and 1400 AD the dominant motions are eastward. The eastward signal at 45° N captured in Fig. 2a is also observed in Fig. 3 from 1650 AD onward. At the same latitudes in the Southern hemisphere, large parts of the time period are white, partly a consequence of the sparsity of the data which do not resolve azimuthal motions very well, but possibly also a reflection of a lack of such consistent motions. Episodes of eastward motions near 800 AD and westward motions near 1300 AD are observed in Fig. 3, but our confidence in these features is low. Close to the equatorial region, westward motions are observed from 1400 AD onward, in agreement with the historical observations. An eastward motion may be present at low latitudes near 1200 AD. At earlier times, the limitations in CALS7K.2 do not allow to retrieve azimuthal motions in the equatorial region with confidence. Hence, although Fig. 1 may suggest that the historical pattern of equatorial westward motions in the Atlantic hemisphere may have persisted for the last 3000 yr, we are unable to confirm this robustly.

4. Latitudinally averaged azimuthal drift

To illustrate the global importance of eastward versus westward motions over the last 3000 yr, we construct a latitudinal average of the angular motion as a function of time. To do this, we compute the angular displacement $\omega(\theta) = V_\phi(\theta)/(r_b \cos\theta)$ at each latitude θ, where $V_\phi(\theta)$ is the azimuthal motion from Fig. 3 and r_b is the radius of the core. Our latitudinal average is limited to

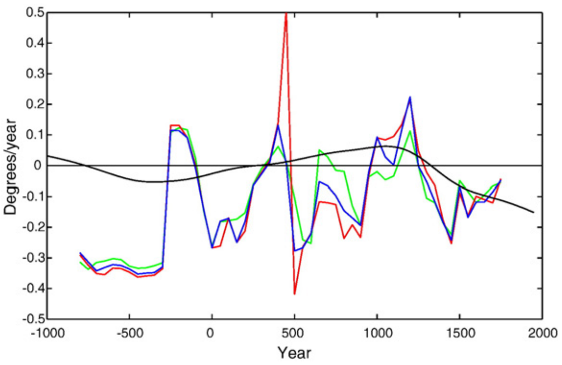

Fig. 4. Latitudinally averaged azimuthal angular drift rate for cutoff values of $p_c = 0.7$ (green), $p_c = 0.9$ (blue) and $p_c = 1.0$ (red). The black line is the globally averaged drift rate from the study of Dumberry and Bloxham [22].

the range between 70° N and 70° S, and excludes the regions on Fig. 3 that are below the power threshold p_c. This is not meant to be a precise determination of the global drift, especially before 1000 AD where little information below 30° N contributes, but simply to illustrate the gross trend in its dominant part. In Fig. 4 we show the latitudinally averaged drift rate as a function of time for different values of the cutoff constant p_c. There is a general dominance of eastward drift between 1000 AD and 1400 AD at a rate of 0.1–0.2° yr^{-1}. A global westward motion seems to have been dominant at other times, except perhaps near 200 BC and 400 AD. The global drift from 1400 AD onward is westward, at rates similar to the surface westward drift of 0.2° yr^{-1} observed during historical times. We also show on Fig. 4 the globally averaged drift rate from the study of Dumberry and Bloxham [22] obtained by a regularised inversion for longitudinally averaged core flows consistent with the secular variation of CALS3K.2 (a similar model to CALS7K.2 but restricted to the last 3000 yr). Because only the axisymmetric part of the flow was retained in this inversion, the results can equally be interpreted as representing the time-dependent globally averaged azimuthal motion of magnetic field features. We note a general agreement in the broad trend for the last 1000 yr: eastward drift prior to 1400 AD and westward drift after that.

We note also that the amplitudes are comparable when one considers that our recovered azimuthal motions usually cover only 180° in longitude and zonally averaging would decrease inferred global speed by a factor 2. Thus our study gives results that are consistent with those of Dumberry and Bloxham [22], but indicates that the zonally averaged motions they discuss consist of azimuthal motions of field features that are occurring in geographically localised regions of the CMB.

5. Azimuthal field motions under Europe

Although westward motions have received much greater attention in the literature, evidence of eastward field motions have been reported before. On an inclination–declination plot, a so-called Bauer plot, the magnetic field recorded at an individual site should trace a segment of an ellipse in a clockwise direction if the underlying azimuthal motion of the non-dipole field is westward. Conversely, eastward motion should result in an anti-clockwise ellipse segment. This is known as Runcorn's rule [35], and although it has been shown to fail in certain situations [36,37], it remains a useful way to infer the direction of motion from the geomagnetic record at one location. Based on this rule, many cases of eastward motions have been reported, the best evidence for a single site possibly being the record at Mono Lake, California, 24 000 yr ago [38]. During the past 3000 yr, the strongest case for eastward motion is under Europe between 900 AD and 1350 AD [19–21]. This is illustrated in Fig. 5, where we show the change in the magnetic field recorded in Europe on a Bauer plot, as inferred from a recent data compilation [39]. The trajectory of the curve is distinctly anti-clockwise

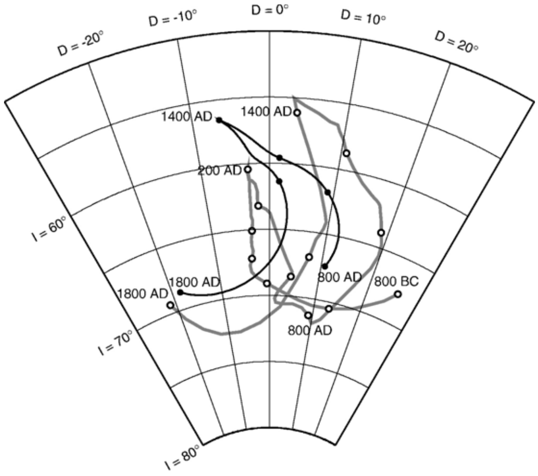

Fig. 5. The smoothed directional variations of the geomagnetic field in Paris (grey curve) between 800 BC and 1800 AD presented by Gallet et al. [39] based on a compilation of observations in Western Europe. The predicted directional variations in Paris (black curve) when the field given by CALS7K.2 at 800 AD is advected by a rigid azimuthal flow, eastward between 800–1400 AD and westward between 1400–1800 AD. A linear drift rate of −0.0115°/yr in declination was added to the integration result. The knots on each curve are separated by 200 yr. (For a prediction of the archaeomagnetic field model itself, see Fig. 3 of Gallet et al. [39].)

between 800 AD and 1400 AD, whereas after 1400 AD it becomes clockwise.

Our results in Sections 2 and 3 show the details of how changes in the direction of azimuthal motions of field features at the CMB have occurred during the past 3000 yr under Europe and thus provide an explanation for the behaviour of the magnetic vector on the Bauer plot of Fig. 5. This can best be seen by considering our time–longitude plots near Europe, for instance at 60° N (Fig. 1a). We have reproduced this plot on Fig. 6, where we have also traced the succession of eastward and westward motion suggested by the pattern of the positive field anomaly. One has to be careful in mapping changes in the magnetic field vector at the CMB directly to the changes taking place at the surface: the field at one site at the surface results from the integrated effect of a broad region of the CMB underneath. Nevertheless, the successive eastward and westward motion observed in Fig. 6 would likely be observed in the inclination–declination variations at the surface in Europe (near longitude 0° E). The azimuthal motion is westward between 200 AD and 750 AD, eastward between 750 AD and 1400 AD, and westward after 1400 AD.

To confirm that a change in the direction of the mean azimuthal motion at the CMB can explain the secular variation of the field shown in Fig. 5, we performed the following experiment. We took the field at the CMB in 800 AD from CALS7K.2 and integrated forward in time the changes produced by a rigid azimuthal flow at the surface of the core, eastward at a rate of 0.26° yr^{-1} until 1400 AD, and westward after that date at a rate of 0.48° yr^{-1}. At the latitude of Europe, these rates correspond to speeds of 10 km yr^{-1} and 19 km yr^{-1}, respectively, and are consistent with the values in Fig. 3. The predicted change in the field under Europe resulting solely from this simple dynamical prescription is plotted on the Bauer plot of Fig. 5. To improve visibility, we added an arbitrary linear drift in declination of -2×10^{-4} rad yr^{-1} ($-0.0115°$ yr^{-1}); without it, the trajectory after 1400 AD is simply the reverse of that prior to the change in flow direction. This simple dynamical model is capable of reproducing a large part of the observations. It clearly captures the anti-clockwise and clockwise displacement respectively before and after 1400 AD. The full details of the evolution of the field are obviously also influenced by dynamical effects not modelled by our simple rigid advection model, including for instance growth and decay of field features. The linear drift in declination that we have added is intended partly to represent these unmodelled effects. We have deliberately chosen a drift rate which gives a close match with the data curve; however, the largest part of the changes are produced by the underlying azimuthal motions, including the sense of rotation on the Bauer plot.

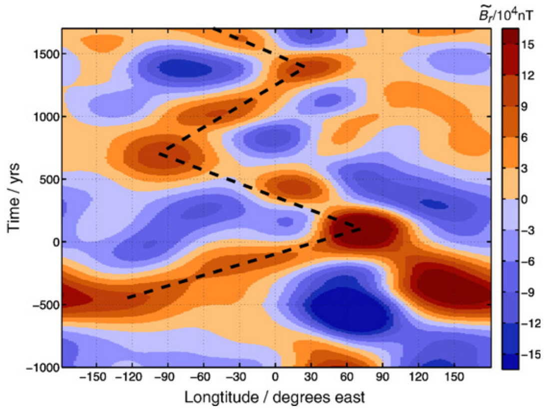

Fig. 6. Time–longitude plot of the radial part of CALS7K.2p at the CMB at 60° N. The black dotted line follows the azimuthal motion of a positive field feature. The times of changes in the direction of motion are roughly at 200 AD, 800 AD and 1400 AD.

The times at which sharp changes, or cusps, are observed on the Bauer curve of European data (at 200 AD, 800 AD and 1400 AD on Fig. 5) have been referred to as "archaeomagnetic jerks" [39]. These dates coincide with the times at which we observe a transition in the direction of the moving field features at the CMB (Fig. 6). Thus, it suggests that "archaeomagnetic jerks" at European sites delineate intervals of oppositely directed mean azimuthal motion in a broad region of the CMB underneath. We note that the cusps produced by our simple scenario do not require that the transition in the direction of motion occurs sharply. An identical black curve as that shown in Fig. 5 can be generated with an underlying flow changing linearly from eastward to westward as long as the transition takes place at 1400 AD (although the knots separating the 200 yr intervals in the curve would be displaced). The key ingredient to generate the cusps on Fig. 5 is not the sharpness of the change, but the change in the direction of motion itself, so long as the amplitude of this directional change is sufficient for this process to dominate the observed secular variation. We note however that the knots delineating 200 yr intervals on the data curve are spaced regularly prior to and after 1400 AD, indicating that the transition must have occurred over a timescale of 100 yr at most. This is consistent with the timescale of the change in the direction of motion observed in Fig. 6.

6. Discussion and conclusion

We have shown that CALS7K.2 suggests that both eastward and westward motions of magnetic field features at the CMB have occurred in the past 3000 yr. The clearest azimuthal motions are observed at mid-latitudes in the Northern hemisphere. At the same latitudes in the Southern hemisphere, we do not find strong evidence of analogous motions, although the poorer data coverage there prevents us from concluding that they are absent.

These Northern hemisphere motions are related to the displacements and distortions of the two high-latitude magnetic flux concentrations, one under Canada and the other one under Siberia [40,41]. Indeed, the two broad longitudinal regions of the separate episodes of azimuthal motions observed in Fig. 1a and b are geographically consistent with these locations. The flux concentrations possibly owe their existence to thermal coupling between the geodynamo and the lower mantle and correspond to regions of higher than average heat flux [42,43,26]. They have remained nearly stationary during historical times [40,41], and are observed in the palaeomagnetic record [44]. Over the past few millennia, field models such as CALS7K.2 suggest their presence in the time-averaged magnetic field, yet that their instantaneous location and shape is variable [30,32]. The azimuthal motions that we have captured are a direct consequence of this time-dependency. Our results therefore support the idea that the flux concentrations are not fully "locked" to the pattern of heat flow at the CMB, though they are on a time-averaged sense, as also observed in some numerical simulations [42,43,27]. We believe this to be a robust result for two reasons: first, because our resolution tests indicate that azimuthal motions at the latitudes of these flux concentrations are well resolved; and second, because we found that similar azimuthal motions have occurred during historical times.

The rate of motion associated with each flux patch is variable and sometimes goes to zero. Because of this the globally averaged drift rate that we have compiled is sometimes eastward and sometimes westward. Under Europe, in particular, the direction of the mean azimuthal motion appears eastward until 200 AD, westward between 200 AD and 800 AD, eastward between 800 AD and 1400 AD and westward from 1400 AD onward. Our results are consistent with previous inference of eastward motions of field features under Europe between the 9th and 15th centuries [19–21]. Moreover, because our results are based on a global dataset, and on an actual tracking of moving magnetic field features at the CMB in a model based on these data, we believe they provide definitive evidence that Earth's magnetic field undergoes azimuthal secular variation in both eastward and westward directions.

An important question for the geodynamo is whether these Northern latitudes azimuthal motions are a result of advection of magnetic field features by azimuthal flows, or whether they can be accounted for by azimuthally travelling hydromagnetic waves. As shown in Fig. 4, the azimuthal motions that we have recovered are consistent with those obtained by Dumberry and Bloxham [22]. In that study, it was assumed that the secular variation was due to advection by flow. It was then shown that the amplitude and timescale of the flow variations were consistent with those required to explain the changes in length of day observed over the same time interval [45,46]. Because the mid-latitude azimuthal motions we have identified are consistent with the results of Dumberry and Bloxham [22], we favour an explanation in terms of advection by flow.

Changes in the azimuthal direction of field features are capable of generating cusp-like signatures in inclination–declination (Bauer) plots. Such changes of direction are observed in time–longitude plots of CALS7K.2 at Northern mid-latitudes at times and locations corresponding to observed cusps in Bauer plots from sites in Western Europe. We suggest that the cusps observed in Europe, which have been referred to as archaeomagnetic jerks [39], are caused by a change in the direction of the dominant azimuthal flow near to the core surface in the vicinity of these sites. The change in flow direction does not need to be very sudden but must take place in a timescale of 100 yr or shorter. Archaeomagnetic jerks have not been reported outside of Europe, and so it is unclear at this point whether they are global phenomena. But if our explanation is correct, they should be observed in other places where the secular variation is dominated by a transition in the direction of the underlying azimuthal core flows.

Our results do not provide definitive conclusions on whether the historical equatorial westward motions have been a permanent feature of the secular variation for the past 3000 yr. We do observe westward motions in the latitudinal band between 20° N and 20° S for most of the past 3000 yr. However, we cannot retrieve a signal as robust as during historical times. Further analysis is required to determine whether this is because the equatorial westward motions are indeed an intermittent feature of the geodynamo or whether they are simply not well recovered by CALS7K.2. When equatorial westward motions are observed though, they are best seen in the Atlantic hemisphere, as it is the case for the present-day. If the longitudinal confinement of the motions were purely a consequence of the spatial variations of the geodynamo, we would expect the location of this region to change over such a timescale. The fact that it does not rather suggests a long term influence by the lower mantle. One possibility is that a greatly enhanced electrical conductivity in the lowermost mantle that screens most of the secular variation under the Pacific [47]. However, the amplitude of the required conductivity is incompatible with other aspects of the secular variation, in particular the presence of free torsional oscillations in core flows [48]. A more likely influence of the lower mantle is through thermal core–mantle coupling. Indeed, some numerical simulations of the geodynamo with a boundary heat flow that reproduces the magnetic flux concentrations at high latitudes also produce a time-averaged equatorial westward flow under the Atlantic hemisphere [26,27]. Alternatively, or additionally, thermal core–mantle interaction may lead to hydromagnetic instabilities being generated preferentially in the Atlantic hemisphere. Our results are therefore generally consistent with the idea that thermal core–mantle interactions influence the geometry of the observed field motions at the CMB.

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