The Westward Drift and Geomagnetic Secular Change

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Summary

Short-term fluctuations in the length of the day on the order of a decade are discussed in relation to fluctuations in westward drift of the outer part of the Earth's core. Decreases in the Earth's rotation rate noted near 1910 and 1965 are shown to be correlated with decreases in westward drift of the Earth's magnetic eccentric dipole, which probably originates fairly deep within the Earth's core. If the outer 200-km thickness of the core moves approximately as does the eccentric dipole field, the changes in angular momentum implied for this part can explain the observed changes in the length of the astronomical second, on the basis of conservation of angular momentum. Other estimates of westward drift in the core based on higher-degree harmonic terms give a lower westward drift, and also seem to show less precision in the estimates of flow in the core. These discrepancies are unexplained.

Since quite early times it has been known that the Earth undergoes several small and little-understood motions additional to its motion about the Sun, the precessional motion, and the daily rotation (Munk & MacDonald 1960). Astronomical observations on the Moon and stars during the past century have shown that the Earth's rotation is non-uniform (Brouwer 1952). Since the Earth's total angular momentum changes very slowly during centuries of time, effects noted during only a few decades suggest that compensatory motions within the Earth's interior would seem required when fluctuations in surface rotation are observed (Munk & Revelle 1952; Vestine 1952). The main possibility for such motions, which could yield internal angular momentum changes within decades, would seem to be in the Earth's fluid metallic core. Accordingly it is of interest to estimate possible changes in the rotation of the core expected to compensate for fluctuations in angular momentum of the mantle indicated by changes in the length of day. Since the Earth's field is thought to originate in a hydromagnetic core, the geomagnetic field lines may be firmly attached to the surface flow in the core. Therefore, field lines moving about on the Earth's surface may show whether such compensatory motion in the core takes place.

Previous work establishing such connection has unhappily been less certain than desired (Kalinen 1949; Vestine 1952; Smirnov 1965). Vestine (1952) showed that if the Earth's eccentric dipole motion is monitored at five-year intervals since 1840, it undergoes a westward drift of about 0.03°/yr, except for several five-year intervals centred near 1910, for which the westward drift is perceptibly reduced (to less than half), corresponding to an increase in the angular velocity of the core. This occurred at a time when the mantle and crust slowed down, so that the day became longer.
After about 1910 the mantle began to rotate more rapidly, perhaps until about 1935 (Brouwer 1952). The westward drift of the eccentric dipole meanwhile increased.

The effects estimated, however, are rather small and uncertain, and it would be highly desirable to confirm this result by some independent means. It is known, for instance, that though the eccentric dipole result is based on the lower and presumably best-determined harmonic terms of the main field (Chapman & Bartels 1940), the rate of westward drift is different for higher-degree terms in the main field (Bullard & Gellman 1954; Yukutake 1962, 1967; Nagata 1962; Cain, private communication; Richmond 1966). Furthermore, Hide (1966, 1967) points out that the magnetic effects may be due to hydromagnetic waves in the core.

In the present paper we continue the discussion of this matter and examine data on the westward drift of geomagnetism, estimated using more general concepts which provide tentative values for both zonal and non-zonal flow in the core. These new results are not necessarily better than the old, with which they are compared. In another approach we calculate the zonal flow required in the core, using the astronomical data on the rate of the Earth's rotation and assuming the total angular momentum of the Earth is conserved. On this basis the irregularities in drift of the eccentric dipole previously estimated would then require a depth of flow of only 200 km or so in the core. Finally, some possibilities based on use of better timing and the Earth's rotation are discussed along lines recently suggested by Gold (1967) and MacDonald (1967), who propose that rotation times be estimated using point radio sources in space. We begin by discussing possible surface flow in the core, estimated using the more accurate recent data on the geomagnetic field.

In a series of papers we have estimated surface flow for a hydromagnetic core of large magnetic Reynolds number, using values of the main field and its secular change extrapolated to core level (Kahle, Vestine & Ball 1967; Kahle, Ball & Vestine 1967; Vestine, Ball & Kahle 1967). In this work, field diffusion and hydromagnetic wave motion is neglected, the surface velocity $v$ being given by

$$\frac{\partial B}{\partial t} = \nabla \times (v \times B), \tag{1}$$

where $B$ is the magnetic field and $t$ the time. The values of $v$ are expressed in the form

$$v = r \times \nabla T x - \nabla T \psi, \tag{2}$$

where $r$ is the radial distance from the Earth's centre, $\nabla T$ is the 2-dimensional horizontal gradient, and $\chi$ and $\psi$ are velocity functions expressed in polar coordinates $(r, \theta, \lambda)$ in the form

$$\chi = \sum \sum (A_n^m \cos m \lambda + B_n^m \sin m \lambda) P_n^m(\theta),$$

$$\psi = r \sum \sum (a_n^m \cos m \lambda + b_n^m \sin m \lambda) P_n^m(\theta). \tag{3}$$

The stream function $\chi$, for which fluid flows along lines of equal $\chi$ on the core surface includes the terms in $A_n^0$ comprising the westward drift.

Figs 1–3 show the irrotational flow $\psi$, rotational flow apart from westward drift $\chi - A_n^0$, and the westward drift $A_n^0$, in various colatitudes, respectively, obtained from values of $B$ and $\partial B/\partial t$ for 1960.

If the flow patterns shown persist to some depth in the core, as seems reasonable, their change with time would represent a change in angular momentum, to which motion of the mantle must conform, if compensation is not completed elsewhere in the core. Change in the zonal flow of the core may hence change the rate of rotation of the mantle, and poleward flows along the $\chi$-contours may also shift the north pole of the Earth.

It is not clear that our procedure provides a better numerical value of westward drift given by the terms in $A_n^0$ than does the estimate of the westward displacement.
Fig. 1. Irrotational part of core surface velocity for epoch 1960.

of surface charted data at two epochs (Bullard et al. 1950). This is because the surface motion will be dominated by the second-degree harmonic, whereas near the core the fourth-degree harmonic seems to dominate (Richmond 1966). Our method would seem to afford some hope of improvement over the displacement method using surface charts, if this improvement is not more than offset by the amplification of error inherent in the extrapolation of the field to the core. It is therefore of some interest to compare the values obtained on this basis since 1885 with the astronomical data on the length of the day.

The first column after the date in Table 1 lists departures in the daily rate of rotation of the Earth in milliseconds. Prior to 1950 the values are those estimated from Brouwer (1952). The 1950 value in parentheses is an extrapolation of Brouwer's curve. The departures since 1950, based on the new clocks, are preliminary and were kindly furnished to us by Richard Keating, U.S. Naval Observatory. They indicate a recent, rapid slowing of the Earth's rotation.

The zonal motions of the core, based on the method outlined above, are found from the main field and secular change field coefficients given for various epochs by Vestine et al. (1947), Mauersberger (1952), Jensen & Cain (1962), Leaton, Malin & Evans (1965), and Cain et al. (1967). The westward drifts $w_m$ in Table 1 are derived assuming that the core is coincident with the Earth's surface, and that $w_m$ is equal to $-A_n^5$ in equation (3), the coefficients of $u$ being estimated to degree 4 and order 4 inclusive, using main field and secular change to degree 6 and order 6. Separate
estimates are made of the velocity $w_c$ at the surface of the core by extrapolating the magnetic fields of degree 4 and order 4. These are listed in the next column. The values from magnetic data should represent motion of the core rather than the mantle, and appear to vary inversely with the departures in length of day to about 1950. As the westward motion of the geomagnetic field imbedded in the core increases so that the rate of core rotation is reduced, the rate of mantle rotation is increased, in the sense required for conservation of angular momentum, and is in accord with a previous suggestion based on eccentric dipole motion made by one of us (Vestine 1952). While it is gratifying to note the qualitative agreement, it is necessary to note some grave deficiencies. After 1950 the surface estimates do not agree with the astronomical data, but we may prefer to use the values $w_c$ for the core, which may agree better with astronomy. If we discount the disagreement in 1885, and possibly 1925, which could be due either to poor magnetic data, or to defective astronomical data, it is disturbing to find that results based on two carefully made analyses for 1965 show such glaring disagreement. Here the values of Leaton (7.15 km/yr) and Cain (17.95 km/yr) are unhappily quite different. The result of Cain includes more satellite data of the World Magnetic Survey, and was made for a spheroidal Earth. The fit to main field data is about as good in both cases, so that small differences in secular change may be the cause of the disagreement. It seems clear that the results are somewhat sensitive to differences in the data analysed, even for the same epoch, and
The westward drift

Table 1

<table>
<thead>
<tr>
<th>Date</th>
<th>L.o.d. (ms)</th>
<th>$w_m$ (km/yr)</th>
<th>$w_c$ (km/yr)</th>
<th>$\alpha$ (deg)</th>
<th>$-\alpha$ (10^-3 rad/yr)</th>
<th>$w_{\Delta}$ (km/yr)</th>
<th>$\delta w_c$ (km/yr)</th>
<th>$w_{ca}$ (km/yr)</th>
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<td>35.8</td>
<td>0.39</td>
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<td></td>
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<td>L 7.15</td>
<td>11.4</td>
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<td>2.850</td>
<td>18.2</td>
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Fig. 3. Westward drift component of core surface velocity for epoch 1960.
therefore illustrate the need for more accurate survey data, as was emphasized by Sydney Chapman when he proposed the World Magnetic Survey in 1957.

It may be of interest to comment further on the estimates of westward drift obtained by extrapolating main field and secular change to the core surface. These were found using truncated series taken to degree 4 and order 4 in an effort to improve results, since the higher-degree terms in secular change are likely to be less accurately determined than those of low degree. The results obtained are at variance with one another, and with those for \( w_m \). The latter disagreement, however, can perhaps be discounted, since Richmond (1966) has shown that the angular rate of westward drift depends mainly on that of the second-degree harmonic at the surface of the Earth and upon the more slowly drifting, fourth-degree harmonic near the core. Because of these new results, and for other reasons, it is clear that estimates of zonal flow in the surface of the core, based on using geomagnetic data in equation (1) remain somewhat uncertain.

In the case of the westward drift estimated using the eccentric dipole motion, the results agree somewhat better with those of astronomy. In Table 1, \( \alpha \) is the angular position or east longitude, \(-\alpha\) is the westward angular velocity, and \( w_e \) the westward equatorial drift of the eccentric dipole measured at the Earth's surface. Near 1910 and 1965 the westward drift is reduced to about 11 km/yr and 18 km/yr, respectively (equivalent to eastward acceleration of the core), and these are times when the angular velocity of the mantle determined from the I.o.d. was decreased.

The results for the eccentric dipole can be compared with those from astronomy in another way. The data on I.o.d. in column 1 can be used to estimate the core motion needed to conserve angular momentum, assuming only the outer part of the core to take part in this compensation.

If \( \omega_c, \omega_m \) are the angular velocities of the core and mantle, and \( I_c, I_m \) the respective moments of inertia about the Earth's axis of rotation, we then have

\[
I_c \omega_c + I_m \omega_m = \text{const.} \tag{4}
\]

If \( r_c \) is the radius of the core, we have the eastward surface velocity \( v_c = r_c \omega_c \). Also \( \omega_m = 2\pi/T_m \), where \( T_m \) is the period of rotation of the mantle. Then

\[
\frac{d\omega_c}{dt} = -\left(\frac{I_m}{I_c}\right) \frac{d\omega_m}{dt} \tag{5}
\]

where \( I_m = 7.2 \times 10^{44} \text{g cm}^2 \), \( I_c = 0.85 \times 10^{44} \text{g cm}^2 \) (Munk & MacDonald 1960). Consequently

\[
\frac{dv_c}{dt} = -9.524 r_c \frac{d\omega_m}{dt}, \tag{5}
\]

where

\[
\frac{d\omega_m}{dt} = -\frac{2\pi}{T_m^2} \frac{dT_m}{dt}.
\]

The calculated changes in westward drift \( \delta w_c \), based on the I.o.d. from the first column, are given in Table 1. These have been integrated with respect to time and show the cumulative change from the 1885 value. Next these were adjusted to conform in average magnitude with the observed values \( w_e \) based on eccentric dipole motion, assuming a core depth of zonal flow of about 200 km, and are compared with \( w_e \) in Fig. 4. These are listed in the column \( w_m \) in Table 1. The agreement appears rather good. There may also be evidence of a five-year lag of the core motion relative to the mantle motion, suggesting a time constant of about 5 years, a value possibly corresponding to a mantle conductivity above the core equal to about \( 7.5 \times 10^{-9} \).
The westward drift

Fig. 4. Westward drift velocity at the surface of the Earth from A, change in angular momentum of outer 200-km layer of core necessary to balance l.o.d. change, and B, observed eccentric dipole motion.

e.m.u. (Vestine 1952; Rochester 1960). The time constant agrees also with recent suggestions of Currie (1967). Although the change in mantle motion may in fact precede that of the eccentric dipole, the transmittal of angular momentum across the core mantle interface must occur at the same time as surface motion of the mantle is noted. The 5-year interval would be consistent with the time of propagation of a wave through a substantial part of the core and the mantle.

The present work considers that the magnetic field lines move more or less with the fluid at the surface of the core. Magnetic diffusion at the surface of the core is neglected, which is believed quite satisfactory for the short intervals of time in the Earth’s history considered here. For broad-scale field patterns covering thousands of km, the effective magnetic Reynolds number should be large, so that equation (1) should be useful. Since doing this work, we have noted a paper by Rikitake (1967), who presupposes a 300-gauss $T_2$ toroidal field present near the surface as well, with attention to induction appropriate to smaller magnetic Reynolds numbers, or to flow patterns persisting for a very long time. The flow patterns found near the core surface, however, seem in general to resemble roughly those in Figs 1 and 2, and confirm the upflows near Africa suggested by us and the downflows in the Pacific (Kahle, Vestine & Ball 1967). It is not at all clear that zonal flows at the core estimated using Rikitake’s method would be preferable in studies of the westward drift. For deep-seated sources in the core, such as are probably cogent for the eccentric dipole, there seems little need for revision of our present results.

It should also be emphasized that uncertainties present in Brouwer’s data on the Earth’s rotation are much reduced in the astronomical data of the past decade. Even though these results are preliminary, the use of superior astronomical equipment and clocks now provides considerably greater precision than in the past. These results are likely to improve also in future years, if suggestions such as those of Gold (1967) and MacDonald (1967) incorporating radio sightings on distant radio point-sources can be used in measuring the Earth’s rotation.

In conclusion, we may remark that the marked slowdown in the Earth’s rotation near 1910 might be caused by a change in westward drift of the core, and is in fact correlated with eccentric dipole motion. Evidence of a second slowdown of the mantle during the past few years also appears correlated with changing eccentric dipole motion, adding new support to the concept of fluid flow in the core. Here the
variability in zonal flow may provide a magnetic couple, causing the fluctuations in mantle motion observed by astronomers (Rochester 1960). Estimates of zonal flow in the core based on higher-degree harmonics in the main field and its secular change are made, and though those for the core are qualitatively in fair agreement with those for the eccentric dipole, serious discrepancies in magnitude are unexplained. At least for the present time, the eccentric dipole appears to be a better indicator of changes in the angular momentum of the core than does the surface zonal flow.

It is a pleasure to acknowledge our indebtedness to Dr Richard Ball for helpful discussions during the course of the work.

The Rand Corporation, Santa Monica, California.

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