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# KINEMATIC REVERSAL SCHEMES FOR THE GEOMAGNETIC DIPOLE*

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## ABSTRACT

Fluctuations in the distribution of cyclonic convective cells, in the Earth's core, can reverse the sign of the geomagnetic field. Two kinematic reversal schemes are discussed. In the first scheme, a field maintained by cyclones concentrated at low latitude is reversed by a burst of cyclones at high latitude. Conversely, in the second scheme, a field maintained predominantly by cyclones in high latitudes is reversed by a fluctuation consisting of a burst of cyclonic convection at low latitude.

The precise fluid motions which produce the geomagnetic field are not known. However, it appears that, whatever the details are, a fluctuation in the distribution of cyclonic cells over latitude can cause a geomagnetic reversal.

## I. INTRODUCTION

In a previous paper (Levy 1972, hereinafter called Paper I) we studied stationary solutions of the dynamo equations and showed that cells of cyclonic convection, at any location in the Earth's core, are able to maintain a stationary, dipole magnetic field. While paleomagnetic studies (Runcorn 1955; Van Zijl 1962; Ninkovich *et al.* 1966; Wilson 1966) indicate that the Earth is, in fact, a stationary dipole, they also show that the dipole changes sign "spontaneously" and at random intervals of $10^5$–$10^7$ years.

Normal maintenance of the geomagnetic field is a two-stage process. Nonuniform rotation of the highly conducting liquid core draws the poloidal field into a toroidal magnetic field (Fig. 1); the toroidal field is twisted into meridional loops of poloidal field by cyclonic convective motions in the turbulent core. If the meridional loops have the same sense as the large-scale dipole, then the field is regenerated. In Paper I we pointed out that there generally exist, in the core, regions of normal toroidal flux (where the meridional loops produced from the toroidal field have the same sense as the dipole and hence reinforce it) and regions of reverse toroidal flux (where the meridional loops are of opposite sense and hence degrade the poloidal field). We suggested that the regions of reverse toroidal flux play a central part in the phenomenon of geomagnetic reversals.

Convective overturning in the core is reflected in small-scale inhomogeneities in the magnetic field at the surface of the Earth. Observations suggest that cells of convection are spread randomly throughout the core, that from 10 to 15 are present in the core at a time, and that the lifetime of a cell is typically $10^3$ years (Elsasser 1950). If the cells of convection are statistically independent, then we suspect that occasional large fluctuations in their distribution throughout the core will occur. The purposes of this paper are to investigate the reverse toroidal flux produced by fluctuations and to describe kinematic schemes which will reverse the geomagnetic field.

The dynamo equations are (Parker 1955, 1970; Braginskii 1964*a;* Steenbeck and Krause 1966)

$$\frac{\partial B_\phi}{\partial t} - \eta\left(\nabla^2 - \frac{1}{r^2 \sin^2\theta}\right) B_\phi = B_r\left(\frac{\partial v_\phi}{\partial r} - \frac{v_\phi}{r}\right), \tag{1}$$

$$\frac{\partial A_\phi}{\partial t} - \eta\left(\nabla^2 - \frac{1}{r^2 \sin^2\theta}\right) A_\phi = \Gamma(r, \theta, t) B_\phi(r, \theta, t)\,, \tag{2}$$

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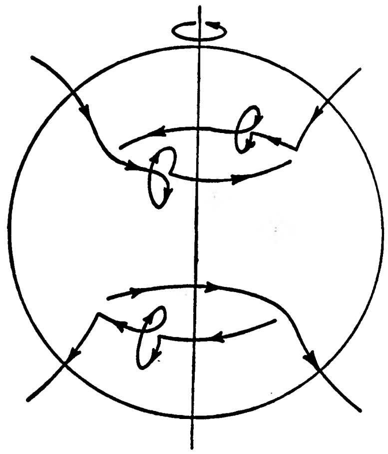


FIG. 1.—In the normal regeneration of the geomagnetic field, large-scale velocity shear stretches the poloidal field into an azimuthal, toroidal field $B_\phi$. Rising cyclones twist $B_\phi$ into poloidal loops of field. If these loops reinforce the original dipole field, then a regenerative dynamo can exist.

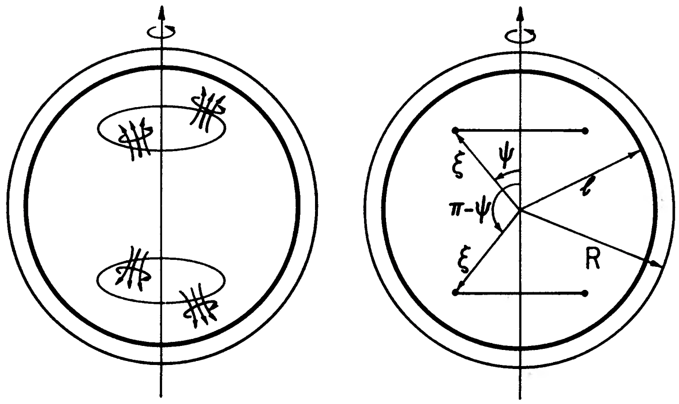
and

$$B_r = \frac{1}{r \sin\theta} \frac{\partial}{\partial\theta} (A_\phi \sin\theta) . \tag{3}$$

The magnetic diffusivity $\eta$ is estimated to be of the order of $10^5$ cm$^2$ s$^{-1}$, in the Earth's core (Elsasser 1950). In order to pursue our investigation of the role of cyclone fluctuations in geomagnetic reversals we will first derive an expression for the toroidal magnetic flux created by a burst of cyclones. As a mathematical convenience we envision a type of fluid motion suggested by Backus (1958). We simulate a fluctuation by bursts (delta functions in space and time) of cyclonic convection and nonuniform rotation interspersed with periods of stasis during which the field decays freely. Since the higher-order modes decay most quickly, our results can be made to converge rapidly by taking the periods of stasis to be of sufficiently long duration. The bursts of motion must then be made vigorous enough to compensate for the decay. While this fluid velocity field is not realized in nature, it makes the mathematics tractable and illustrates the physical principles involved.

## II. THE PRODUCTION OF TOROIDAL MAGNETIC FLUX FROM A BURST OF CYCLONES

Parker (1969) discusses, physically, the production of toroidal magnetic field. Rather than reproduce such a discussion here, we proceed directly to the formal mathematics. As a basis for the calculations of geomagnetic reversal, suppose that, for $t < 0$, the dynamo is operating normally, say in the stationary, dipole state generated by nonuniform rotation and cyclonic convection, treated in Paper I (Fig. 2). At time $t = 0$, turn off the steady nonuniform rotation and cyclonic convection and introduce a strong burst of cyclones at some location which we shall choose later. The result is a sudden generation of poloidal field. Following the burst of cyclones, let the fluid remain at rest for an interval $T$ during which the field decays. At time $t = T$ introduce a strong burst of velocity shear, confined to a spherical surface as in Paper I. The shear stretches the lines of force of the poloidal field and produces a toroidal magnetic field, $\Delta B_\phi$. After the burst of shear, let there be another interval of time $T$, during which the fluid is again at rest and the field decays. At the end of this interval (at $t = 2T$), the normal distribution of cyclones and nonuniform rotation is resumed. As a further simplification we suppose that the bursts of cyclones and shear are so strong that we may neglect the initial magnetic fields present at $t = 0$, compared with the field created by the bursts. Thus, at




(a) (b)

FIG. 2.—(*a*) In these calculations we use the same spatial variation of the fluid velocity that was used in Paper I. Cells of cyclonic convection are confined to two axisymmetric rings, and the nonuniform rotation is confined to a spherical shell. (*b*) The parameters defining the fluid velocity field.

time $t = 2T$, the toroidal field present in the core is essentially $\Delta B_\phi$, due to the burst of cyclones at $t = 0$ and the burst of shear at $t = T$. Equation (18) is an approximate expression for $\Delta B_\phi$; the reader who is not concerned with the details of calculation can skip directly to § III.

To calculate the toroidal magnetic flux produced by a burst of cyclonic convection followed by a burst of shear, consider now a burst of cyclones at $t = 0$, consisting of two axisymmetric rings,

$$\Gamma(r, \theta, t) = \tau a^2 \xi^{-1} \Gamma(r, \theta) \delta(r - \xi) \delta(t) [\delta(\theta - \psi) + \delta(\theta + \psi - \pi)] , \tag{4}$$

located symmetrically about the equatorial plane. Since the cyclonic rotation has opposite sign in each hemisphere,

$$\Gamma(r, \pi - \theta) = -\Gamma(r, \theta) .$$

Putting equation (4) into equation (2) and integrating across $t = 0$, we find that the increment in vector potential, $\Delta A_\phi(r, \theta, 0^+)$, due to the burst of cyclones is

$$\Delta A_\phi(r, \theta, 0^+) = \tau a^2 \xi^{-1} \Gamma(r, \theta) \delta(r - \xi) B_\phi(r, \theta, 0) [\delta(\theta - \psi) + \delta(\theta + \psi - \pi)] . \tag{5}$$

Following the burst of cyclones there is a period of stasis during which the field decays freely. The normal modes of resistive dissipation in a conducting sphere comprise a complete set of functions, and we may expand $\Delta A_\phi(r, \theta, t)$ in that set (Elsasser 1946*a*, *b*, 1947):

$$\Delta A_\phi(r, \theta, t) = \sum_{n,m=1}^{\infty} \Delta A_{nm} j_n(\alpha_{nm} r) P^1{}_n(\cos \theta) \exp(-\eta \alpha_{nm}{}^2 t) . \tag{6}$$

Continuity of the magnetic field at the surface of the conducting sphere, $r = R$, requires that

$$j_{n-1}(\alpha_{nm} R) = 0 . \tag{7}$$

The coefficients $\Delta A_{nm}$ are found from

$$\Delta A_{nm} = \frac{2n + 1}{R^3 j_n{}^2(\alpha_{nm} R) n(n + 1)} \int_0^R dr r^2 j_n(\alpha_{nm} r) \int_0^\pi d\theta \sin \theta P^1{}_n(\cos \theta) \Delta A_\phi(r, \theta, 0^+) . \tag{8}$$

Upon evaluating $\Delta A_{nm}$, we obtain

$$\Delta A_\phi(r,\theta,t) = \sum_{n,m=1}^{\infty} \frac{(4n-1)\tau a^2\xi B_\phi{}^0}{R^3 j_{2n-1}{}^2(\alpha_{2n-1,m}R)n(2n-1)} j_{2n-1}(\alpha_{2n-1,m}\xi)\sin\psi P^1{}_{2n-1}(\cos\psi) \times j_{2n-1}(\alpha_{2n-1,m}r)P^1{}_{2n-1}(\cos\theta)\exp[-\eta(\alpha_{2n-1,m})^2 t]\,. \tag{9}$$

We have already defined $\Gamma \equiv \Gamma(\xi,\psi)$, and $B_\phi{}^0 \equiv B_\phi(\xi,\psi,0)$. Using equations (3) and (9), we find that the radial component of poloidal magnetic field due to the burst of cyclonic motion is

$$\Delta B_r(r,\theta,t) = \sum_{n,m=1}^{\infty} \frac{(4n-1)\tau a^2\xi\Gamma B_\phi{}^0}{rR^3 j_{2n-1}{}^2(\alpha_{2n-1,m}R)n\sin\theta} \times j_{2n-1}(\alpha_{2n-1,m}\xi)\sin\psi P^1{}_{2n-1}(\cos\psi)j_{2n-1}(\alpha_{2n-1,m}r) \times [P^1{}_{2n}(\cos\theta) - \cos\theta P^1{}_{2n-1}(\cos\theta)]\exp[-\eta(\alpha_{2n-1,m})^2 t]\,. \tag{10}$$

At time $t = T$ after the burst of cyclones, a burst of nonuniform rotation occurs, so that

$$\frac{\partial B_\phi}{\partial t} - \eta\left(\nabla^2 - \frac{1}{r^2\sin^2\theta}\right)B_\phi = \tau\gamma l B_r(r,\theta,t)\sin\theta\,\delta(r-l)\delta(t-T)\,. \tag{11}$$

Integrating across $t = T$ and substituting $B_r(r,\theta,T)$, we find that the increment $\Delta B_\phi$ in toroidal magnetic flux due to the burst of cyclones and shear is

$$\Delta B_\phi(r,\theta,T^+) = \frac{\tau^2 a^2\xi\Gamma B_\phi{}^0\gamma l\delta(r-l)}{rR^3} \times \sum_{n,m=1}^{\infty}\left\{\frac{4n-1}{n\sin\theta j_{2n-1}{}^2(\alpha_{2n-1,m}R)} j_{2n-1}(\alpha_{2n-1,m}\xi) \times \sin\psi P^1{}_{2n-1}(\cos\psi)j_{2n-1}(\alpha_{2n-1,m}r) \times [P^1{}_{2n}(\cos\theta) - \cos\theta P^1{}_{2n-1}(\cos\theta)]\sin\theta\exp[-\eta(\alpha_{2n-1,m})^2 T]\right\}\,. \tag{12}$$

Following the burst of shear there is another period of stasis during which the field again decays freely. The normal-mode expansion for the free decay of $\Delta B_\phi$ is

$$\Delta B_\phi(r,\theta,t) = \sum_{i,k=1}^{\infty} \Delta B_{ik} j_i(\beta_{ik}r)P^1{}_i(\cos\theta)\exp[-\eta\beta_{ik}{}^2(t-T)]\,, \tag{13}$$

where

$$j_i(\beta_{ik}R) = 0\,, \tag{14}$$

because $\Delta B_\phi(R,\theta,t) = 0$. The coefficients in the expansion are

$$\Delta B_{ik} = \frac{2i+1}{R^3 j_{i+1}{}^2(\beta_{ik}R)i(i+1)}\int_0^R dr r^2 j_i(\beta_{ik}r)\int_0^\pi d\theta\sin\theta P^1{}_i(\cos\theta)\Delta B_\phi(r,\theta,T)\,. \tag{15}$$

The integration is straightforward; we obtain

$$\Delta B_\phi(r,\theta,t) = \sum_{n,m=1}^{\infty}\sum_{i,k=1}^{\infty}\left\{\frac{2i+1}{R^6 j_{i+1}{}^2(\beta_{ik}R)i(i+1)}\frac{l^2 j_i(\beta_{ik}l)\tau^2\gamma a^2\xi\Gamma B_\phi{}^0}{n j_{2n-1}{}^2(\alpha_{2n-1,m}R)} \times j_{2n-1}(\alpha_{2n-1,m}\xi)\sin\psi P^1{}_{2n-1}(\cos\psi)j_{2n-1}(\alpha_{2n-1,m}l)j_i(\beta_{ik}r) \times P^1{}_i(\cos\theta)\left[\frac{8n^2(2n+1)}{4n+1}\delta_{i,2n} - \frac{4n(2n-1)(2n-2)}{4n-3}\delta_{i,2n-2}\right] \times \exp[-\eta(\alpha_{2n-1,m})^2 T - \eta\beta_{ik}{}^2(t-T)]\right\}\,. \tag{16}$$

Summing over $i$, setting $l = R - \epsilon$, and letting $\epsilon \to 0^+$, we find that

$$
\begin{aligned}
\Delta B_\phi(r, \theta, t) \simeq \sum_{k,m,n=1}^{\infty} & \frac{4l^2\epsilon\tau^2\gamma a^2\xi\Gamma B_\phi{}^0}{R^6} \frac{j_{2n-1}(\alpha_{2n-1,m}\xi)}{j_{2n-1}(\alpha_{2n-1,m}R)} \sin\psi P^1{}_{2n-1}(\cos\psi) \\
\times \Bigg\{ & \frac{\beta_{2n,k} j_{2n}(\beta_{2n,k}r)}{j_{2n+1}(\beta_{2n,k}R)} P^1{}_{2n}(\cos\theta) \exp\left[-\eta(\alpha_{2n-1,m})^2 T - \eta(\beta_{2n,k})^2(t - T)\right] \\
& - \frac{\beta_{2n-2,k} j_{2n-2}(\beta_{2n-2,k}r)}{j_{2n-1}(\beta_{2n-2,k}R)} P^1{}_{2n-2}(\cos\theta) \exp\left[-\eta(\alpha_{2n-1,m})^2 T \right. \\
& \left. - \eta(\beta_{2n-2,k})^2(t - T)\right]\Bigg\} . \qquad (17)
\end{aligned}
$$

We have derived an expression for the toroidal magnetic flux generated by a burst of cyclonic convection, followed, after an interval of time $T$, by a burst of nonuniform rotation. At time $t = 2T$, the distribution of cyclones and shear in the core reverts to its usual state, i.e., what it was before the fluctuation. For the purpose of this discussion of kinematic reversal schemes for the geomagnetic field, we assume that the bursts of cyclones and of shear are arbitrarily strong. Therefore, we presume that $\Delta B_\phi$ overwhelms the toroidal field previously existing (due to motions before $t = 0$). Then when the cyclones and shear relax back to normal, at $t = 2T$, the toroidal field is given by $\Delta B_\phi(r, \theta, 2T)$.

If the cyclonic convective cells in the Earth's core are statistically independent and have a typical lifetime of $10^3$ years, then we may reasonably consider this interval to be a relaxation time, characteristic of the distribution of cyclones in the core. Under this assumption, a fluctuation in the distribution of cyclones lasts about $10^3$ years before the core relaxes back to its average state. Our purpose in considering a dynamo maintained by intermittent fluid flow is to facilitate the rapid convergence of equation (17). In particular setting $T = 10^3$ years, it is sufficient to carry the summation in equation (17) only over $k, m, n = 1, 2$ in order to approximate $\Delta B_\phi(r, \theta, 2T)$. Inclusion of higher-order terms does not appreciably alter the results presented here.

For convenience, we set $R = 1$ in the approximate expression for $\Delta B_\phi(r, \theta, 2T)$; then

$$
\begin{aligned}
\Delta B_\phi(r, \theta, 2Y) \approx\ & 12l^2\epsilon\tau^2\gamma a^2\xi\Gamma B_\phi{}^0 \sin^2\psi \sin\theta\cos\theta \\
\times \Bigg\{ & \Bigg[\frac{j_1(\alpha_{11}\xi)}{j_1(\alpha_{11})} e^{-43Y} + \frac{j_1(\alpha_{12}\xi)}{j_1(\alpha_{12})} e^{-73Y} \\
& - \left(\tfrac{5}{2}\cos^2\psi - \tfrac{1}{2}\right)\left(\frac{j_3(\alpha_{31}\xi)}{j_3(\alpha_{31})} e^{-66Y} + \frac{j_3(\alpha_{32}\xi)}{j_3(\alpha_{32})} e^{-116Y}\right)\Bigg] \\
& \times \left[\frac{\beta_{21} j_2(\beta_{21}r)}{j_3(\beta_{21})} + \frac{\beta_{22} j_2(\beta_{22}r)}{j_3(\beta_{22})} e^{-50Y}\right] \\
& + \left(\tfrac{5}{2}\cos^2\psi - \tfrac{1}{2}\right)\left(\tfrac{35}{2}\cos^2\theta - \tfrac{15}{2}\right)\left[\frac{j_3(\alpha_{31}\xi)}{j_3(\alpha_{31})} e^{-100Y} + \frac{j_3(\alpha_{32}\xi)}{j_3(\alpha_{32})} e^{-150Y}\right] \\
& \times \left[\frac{\beta_{41} j_4(\beta_{41}r)}{j_5(\beta_{41})} + \frac{\beta_{42} j_4(\beta_{42}r)}{j_5(\beta_{42})} e^{-73Y}\right]\Bigg\} . \qquad (18)
\end{aligned}
$$

In equation (18), $Y$ is time measured in units of $10^{12}$ seconds.

## III. KINEMATIC REVERSAL SCHEMES

Ignorance of the actual fluid dynamics of the Earth's core prevents us from asserting the details of normal geomagnetic regeneration. In the case of geomagnetic reversals the problem is even more acute, for here we are dealing with departures from the normal stationary state. Therefore, we investigate specific kinematic schemes in an attempt to understand the generic types of fluctuations, in the distribution of cyclonic cells, which can reverse the sign of the geomagnetic dipole.

We identify two basic reversal schemes. In the first scheme, the dipole field is maintained by cyclonic convection concentrated at low latitudes. A fluctuation resulting in a large number of cyclones falling in high latitudes suffuses the low-latitude region with reverse toroidal flux. Normal regenerative low-latitude cyclones then create a dipole field with sign opposite to the original field. In the second scheme the field is maintained normally by cyclones concentrated at high latitudes. In this case, the low-latitude region of the core normally contains reverse toroidal flux. A fluctuation such that a large number of cyclones appears at low latitudes directly produces poloidal field with sense opposite to the large-scale dipole field, thereby causing the dipole field to change sign.

### *a) Low-Latitude Maintenance, High-Latitude Reversal*

Suppose that a dipole field is maintained by cyclonic convection concentrated at low latitude, as shown in Figure 3*a*. Calculations in Paper I show that the entire core then contains normal toroidal flux. Consider now a fluctuation in the cyclone distribution so that a large number of cyclones occur at high latitude. From equation (18) we find the toroidal flux produced by this burst. In Figure 3*b* the shaded area represents the reverse flux 2000 years after a burst of cyclones at $\xi = 0.8$, $\psi = 15°$, $165°$. The poloidal field produced by a cell of cyclonic convection is proportional to $B_\phi$ at the location of the cell (see eq. [5]). Therefore, subsequent low-latitude cyclones, which fall in the region of reverse flux, produce poloidal field with sense opposite to the original dipole.

The dynamo equations (1)–(3) are homogeneous in magnetic field quantities. This reflects the fact that if a magnetic field is generated by a dynamo, then the same field with opposite sign is equally well generated by the same fluid motions. Therefore, once a fluctuation changes the sign of the geomagnetic dipole, the original distribution of cyclonic velocities maintains the reversed field until another fluctuation flips it again.

### *b) High-Latitude Maintenance, Low-Latitude Reversal*

In Paper I we pointed out that stationary dynamos generally produce regions of reverse toroidal flux in the core, as well as regions of normal toroidal flux. In Figure 4*a*, the shaded area indicates the region of reverse toroidal flux associated with a dipole field maintained by rings of cyclonic convective cells at $\xi = 0.7$, $\psi = 18°$, $162°$. A fluctuation putting a large burst of cyclones in the low-latitude region of reverse toroidal flux immediately produces poloidal field with sign opposite to the original dipole (Fig. 4*b*). We find from equation (18) that it also floods the entire core with reverse toroidal flux so that subsequent high-latitude cyclones produce a dipole field opposite to the original (Fig. 4*c*) and maintain it until the next large fluctuation in the distribution of cyclones brings about yet another reversal.

## IV. DISCUSSION

We have described two kinematic schemes by which fluctuations, in the distribution of cyclonic cells in the Earth's core, can reverse the stationary geomagnetic dipole. In one scheme, a field maintained by low-latitude cyclones is reversed by a large burst of cyclones at high latitudes. In the other scheme, a field maintained by cyclones concentrated at high latitudes is reversed by a fluctuation consisting of a large burst of cyclones at low latitudes. We doubt that either of these situations is an accurate reflection of the normal regenerative state of the geomagnetic dynamo. (In fact, calculations in Paper I indicate that it is mid-latitude convection which most easily maintains a dipole field.)

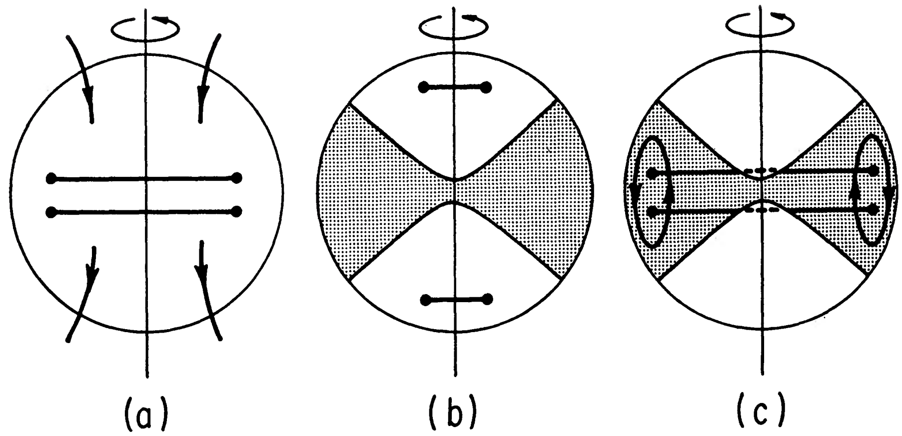



FIG. 3.—(*a*) A dipole field maintained by cyclones concentrated at low latitudes produces normal toroidal field throughout the core. (*b*) A fluctuation in the distribution of cyclones, consisting of a large burst of high-latitude cyclones, produces a region of reverse toroidal flux at low latitude (*shaded area*). (*c*) Subsequent low-latitude cyclones then generate poloidal field with sense opposite to the original dipole, thus reversing the dipole field.

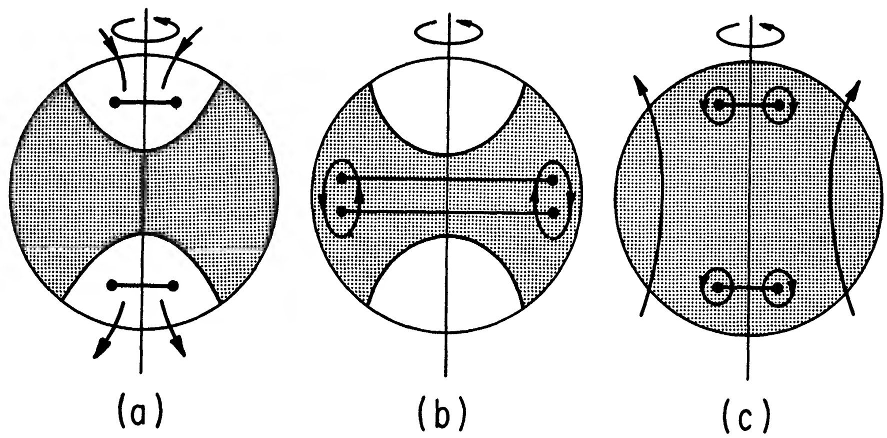



FIG. 4.—(*a*) A dipole maintained by cyclones concentrated at high latitudes produces both normal and reverse toroidal flux in the core. Shaded region represents reverse toroidal flux. (*b*) A burst of low-latitude cyclones produces poloidal field with sense opposite to the original dipole. (*c*) It also floods the entire core with reverse toroidal flux so that subsequent high-latitude cyclones then maintain the reversed field.

However, it appears that, whatever the actual details of geomagnetic generation, a fluctuation in the distribution of cyclones over latitude can reverse the stationary dipole field.

Nagata (1968) has proposed that cells of convection equally distributed around the Earth's rotation axis cannot maintain a dipole field and that occasional, axially uniform distributions of convective cells lead to degeneration and reversal of the field. Since the nonalignment of the magnetic and rotation axes is apparently due to axially nonuniform distribution of convective cells (see a discussion in Parker 1969), Lilley (1970) proposed that a correlation exists between alignment of the two poles and magnetic reversal events. In the case of the rotating Earth, however, the Coriolis force causes convection to be cyclonic. Then axially uniform distributions of cells do regenerate the field so that the proposals of Nagata and Lilley do not seem applicable.

Cox (1968, 1969) asserted that the Earth's dipole normally oscillates sinusoidally with an amplitude of 50 percent of its average intensity. He went on to suggest that interactions between the oscillatory dipole and random fluctuations in the nondipole part of the field cause geomagnetic reversals. The oscillatory nature of the Earth's dipole is not well founded in theory or observation; so it is difficult to assess the validity of this model. Cox's discussion is essentially a statistical one; he does not consider the nature of the fluid motions which can reverse the field. A discussion of the actual role that fluctuations in the fluid motion might play in geomagnetic reversals has been given by Parker (1969). Parker's calculations with nonuniform rotation concentrated at the equator, near the surface of the core, indicated that high-latitude cyclones cannot maintain a dipole field. He suggested that an absence of cyclones from low latitudes causes the field to degenerate and reverse. We have seen from the present calculations and from Paper I that, with a more reasonable, broad distribution of shear, cyclones concentrated at any location in the core are regenerative. Moreover, we have seen that even though cyclones concentrated anywhere in the core are regenerative, fluctuations in the distribution of cyclones can precipitate a reversal of the stationary field.

On the basis of calculations with flat slabs of fluid, several authors (Braginskii 1964*b;* Parker 1971) have suggested that a change in the *level* of turbulence in the core can cause the geomagnetic field to go into an oscillatory state. Then, when the level of turbulence settles back to normal, stationary maintenance of the field proceeds with whatever sign the field has at the time, thereby accounting for geomagnetic reversals. This is an alternative explanation for geomagnetic reversals.

Fluctuations in the distribution of statistically independent cyclones throughout the Earth's core have been discussed by Parker (1969) and Cox (1970). They found the frequency of large fluctuations to be, on the average, several per $10^6$ years. This is in good agreement with the observed frequency of geomagnetic reversals.

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