Influence of the Earth's inner core on geomagnetic fluctuations and reversals

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In view of its relatively small size (one-third the radius of the outer core), many geodynamo models neglect the inner core entirely[1], or otherwise treat it as a non-conducting insulator[2,3]. In a previous steady-state model[4], we considered some effects of a finitely conducting inner core, in particular the resulting electromagnetic coupling between inner and outer core. Here we include a prescribed buoyancy force, which is geophysically more realistic, and also yields time-dependent rather than time-independent solutions. The field in the finitely conducting inner core does not then adjust instantaneously to the field in the outer core, but has a diffusive timescale of its own of a few thousand years. Rather large, rapid fluctuations in the outer core are then effectively averaged out by the inner core, producing a relatively stable external dipole field. We speculate that a geomagnetic reversal could only occur as a result of a particularly large fluctuation, large enough and lasting long enough to reverse the field throughout the inner core as well.

In our previous finitely conducting inner-core model[4], we pointed out that the magnetic field in the inner core cannot be dealt with merely by imposing appropriate boundary conditions on the outer core, because it now has a diffusive timescale of its own, and is thus determined not only by changes on the boundary, but also by its own past history. But as the solutions we ultimately obtained were all steady-state, the potential presence of this new timescale was of rather limited significance. In this work it plays an important role. (There is another new timescale associated with the inner core, the inertial timescale of torsional oscillations. This timescale, however, is typically a few years[5] rather than a few thousand years, and so we filter it out by neglecting inertia as before.)

Let the large-scale axisymmetric magnetic field be $\mathbf{B}_i$ in the inner core and $\mathbf{B}_o$ in the outer core, and let $\mathbf{U}$ be the large-scale axisymmetric fluid flow. Denoting the unit vector parallel to the rotation axis by $\hat{\mathbf{k}}$ and the radial vector by $\mathbf{r}$, the momentum equation in the outer core is then

$$2\hat{\mathbf{k}} \times \mathbf{U} = -\nabla p + E\nabla^2\mathbf{U} + (\nabla \times \mathbf{B}_o) \times \mathbf{B}_o + \Theta\mathbf{r} \qquad (1)$$

representing a balance of forces between the Coriolis (rotational) force on the left-hand side and, respectively, the gradient of the pressure p, viscous, Lorentz (magnetic), and buoyancy forces on the right-hand side. $\Theta = -\Theta_0 r \cos^2\theta$ is the kinematically prescribed buoyancy force, chosen to drive a thermal wind essentially independent of the co-latitude θ. Considering that the geodynamo is ultimately driven by compositional or thermal buoyancy forcing, the inclusion of such a force is geophysically more realistic, although ideally the form of this force would also be dynamically determined rather than kinematically prescribed. The Ekman number E measures the ratio of viscous to Coriolis forces[6]. In the Earth's outer core, E is $0(10^{-12})$ or so, indicating that viscous forces are very small throughout the bulk of the core; we take E to be as small as is numerically possible[7], which here unfortunately is no smaller than 10^{-3}, although this appears to be small enough to be in the asymptotic regime.

The mean-field induction equation is

$$\frac{\partial \mathbf{B}_i}{\partial t} = \nabla^2\mathbf{B}_i \qquad (2)$$

in the inner core, and

$$\frac{\partial \mathbf{B}_o}{\partial t} = \nabla^2\mathbf{B}_o + \nabla \times (\alpha\mathbf{B}_o) + \nabla \times (\mathbf{U} \times \mathbf{B}_o) \qquad (3)$$

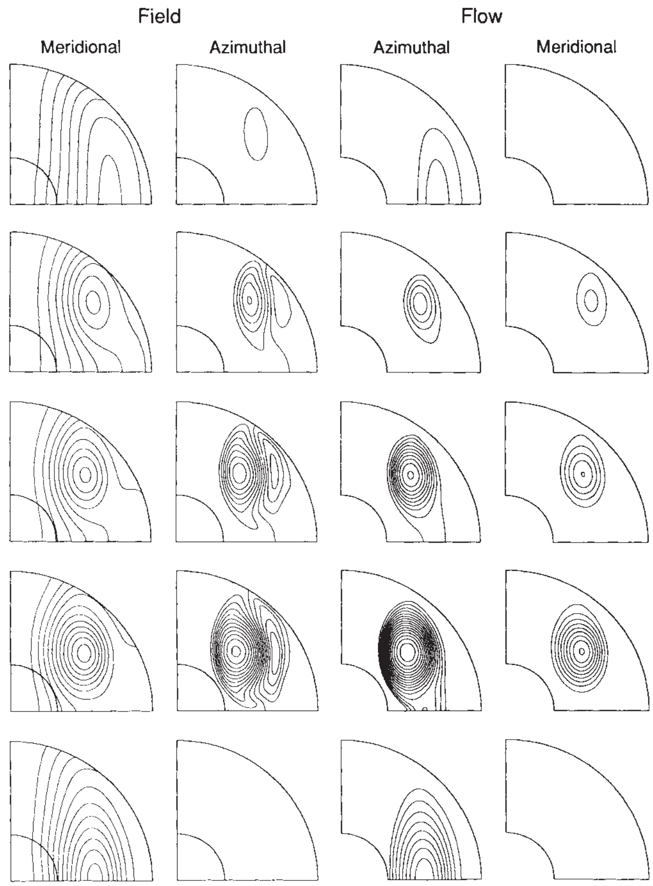

FIG. 1 From left to right, contour plots of the streamfunction of the meridional field, the azimuthal field, the azimuthal angular velocity, and the streamfunction of the meridional velocity for five (from top to bottom) uniformly spaced time intervals throughout the period of 0.22, ~13,000 yr in real time. Contour intervals of 1/2, 1, 50 and 5. The axis of rotation is vertical, and all quantities are axisymmetric about it. The ratio of inner- to outer-core radius, r_i/r_o, is 1/3.

in the outer core. The $\nabla^2\mathbf{B}$ terms represent diffusion of the field throughout the entire core, $\nabla \times (\mathbf{U} \times \mathbf{B}_o)$ represents the inductive effects of the large-scale axisymmetric fluid flow in the outer core and $\nabla \times (\alpha\mathbf{B}_o)$ represents the (parameterized) inductive effects of the small-scale non-axisymmetric fluid flow in the outer core. The value of α, which is in some sense a measure of the departure of the flow from axisymmetry, was previously[4] taken to be the scalar $\alpha_0 \cos\theta$; we retain the same spatial dependence but now take α to be a tensor by including only that component which regenerates meridional (in the planes of lines of longitude) from azimuthal (parallel to lines of latitude) field. The azimuthal field is thus not regenerated from the meridional by the α-effect, but by the above thermal wind by means of the so-called ω-effect[6].

Fixing $\Theta_0 = 200$, and incrementally increasing α_0, the onset of dynamo action occurs at $\alpha_0 \approx 8$, in the form of dynamo waves propagating from the equator to the pole. A secondary, symmetry-breaking bifurcation occurs at $\alpha_0 \approx 12$. The dynamo waves are then no longer oscillations about a zero time-average, but about a non-zero time-average. This bifurcation sequence corresponds exactly to the viscously limited solutions obtained previously[1] in the absence of an inner core, and so the presence of the inner core does not appear to be particularly significant at this stage.

A new and rather interesting type of solution does occur, however, if α_0 is further increased to $\alpha_0 \geqslant 40$. Figure 1 shows one period of the resulting solution at $\alpha_0 = 50$. Contour plots of the field and the flow are shown at five uniformly spaced time

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intervals throughout the oscillation of period 0.22, or ~13,000 yr in real, dimensional time[6]. Note how virtually the entire dynamo process is confined to the region outside the inner-core tangent cylinder. We previously[4] pointed out that in the limit of vanishing viscosity the field had to adjust to have a vanishing electromagnetic torque on the inner core (see also ref. 8), and that it seemed to do this by expelling the azimuthal field from the inner core. Here it seems to adjust by expelling the azimuthal field not just from the inner core, but from the entire region inside the inner-core tangent cylinder as well.

The solution shown in Fig. 1 starts out at the beginning of the periodic cycle with some meridional field and azimuthal flow, but essentially no azimuthal field or meridional flow. As time progresses, the azimuthal flow then gradually increases, and in the process draws out the meridional field to generate azimuthal field. The maximum amplitude of the azimuthal flow is quite large; one circuit in longitude is completed in ~1,000 yr, which is comparable to the observed westward drift[9,10] (and indeed this azimuthal flow is in the westward direction). The azimuthal flow contours are closely aligned with the meridional field contours during most of the cycle, a feature also seen in model-Z dynamos[11]. In consequence, the azimuthal flow is rather inefficient at drawing out the meridional field, so the azimuthal field strength is not simply the (large) magnetic Reynolds number times the meridional field strength. Because of this, our model has a smaller azimuthal field than has sometimes been postulated in the outer core[6]. Our model also shows a sudden collapse of field strength (again in about 1,000 yr, less than 1/10 of the total period), after which the cycle begins anew. This collapse appears to be due to the build-up of a misalignment of the meridional field and the azimuthal flow (perhaps due to the enhanced meridional flow); the magnetic tension associated with the meridional field then suddenly brakes the azimuthal flow.

So, we observe in Fig. 1 a periodic solution to the dynamo equations (1)–(3) that shows very substantial and occasionally very rapid fluctuations. If one now considers the only feature of this solution that would be directly observable in the real geodynamo, namely the external potential field (to which the meridional field matches) these fluctuations are not nearly so substantial. Figure 2 shows the (non-dimensional) dipole moment of this solution as a function of time; for comparison, the Earth's dipole moment in these units would be about 0.2, so the solution obtained here is unfortunately rather large. Although the solution within the outer core undergoes fluctuations of a full order of magnitude, at the core–mantle boundary its variation is considerably less. Note that the meridional field lines that emerge at the core–mantle boundary are largely the same field lines that also thread the inner core (note, for example, the bottom left panel of Fig. 1); that is, the structure of the field is such that the inner core and the mantle are more closely linked than one might think. This is the stabilizing role we envisage for the inner core; it has a diffusive timescale of its own which is comparable to the rapid fluctuations in the outer core, and effectively averages these fluctuations out to produce a much more stable external field than is typically obtained in models without an inner core[1]. Indeed, fluctuations in the external dipole moment of the same relative magnitude (and occurring on the same 10–20 × 10^3 yr timescale as that obtained here), have been observed in the geomagnetic record[12].

To provide evidence that these solutions really are controlled by the inner core, a number of runs were also done with radius ratios (r_i/r_0), ranging from 1/4 to 1/2. The results show that as the location of the inner-core tangent cylinder changes with changing radius ratio, the dynamo process is consistently confined to the region just outside that cylinder. Figure 3 shows one timestep of the solution for a radius ratio of 1/2. At radius ratios of 1/4 or less, this solution ceases to exist. Not surprisingly, if the inner core becomes too small it can no longer control the dynamics. Finally, the fact that it is the location of the inner-core tangent cylinder that controls these solutions proves that rotational forces are considerably more important than viscous forces[7], that is, that our value of 10^{-3} for the Ekman number is sufficiently small.

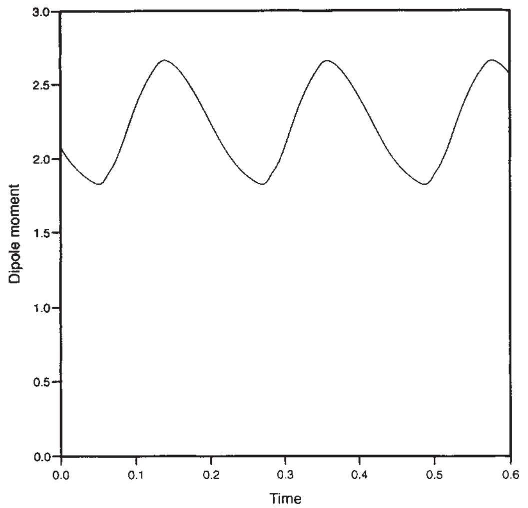

FIG. 2 The external dipole moment as a function of time. Again, the period of 0.22 is ~13,000 yr in real time, and the Earth's dipole moment in these units would be about 0.2.

Considering that the geodynamo model presented here is only an axisymmetric, mean-field model, one should not read too much into the specific details. This model is not intended to be a precise, quantitatively accurate model of the geodynamo, and in view of the rather large external dipole moment it clearly is not. Nevertheless, it demonstrates quite clearly that the presence of the inner core can significantly influence the dynamo processes in the outer core. There is also direct observational evidence for this[13]; the magnetic flux at the core–mantle boundary in the polar regions is lower than that of a pure dipole, a feature that is produced by our results (Fig. 1).

Furthermore, the fact that one can obtain solutions showing such large fluctuations within the outer core, and still maintain a relatively stable external dipole moment, suggests the following plausible reversal mechanism: instead of an exactly periodic solution, as obtained here, imagine a quasi-periodic solution. If a larger than average fluctuation occurred, large enough and lasting long enough to reverse the field in the inner core, the whole field might reverse, but still be relatively stable both before and after. We have demonstrated here that the stabilizing effect of the inner core can prevent most fluctuations from leading to reversals, but if a particularly large fluctuation does lead to a reversal, the inner core will of course equally effectively stabilize

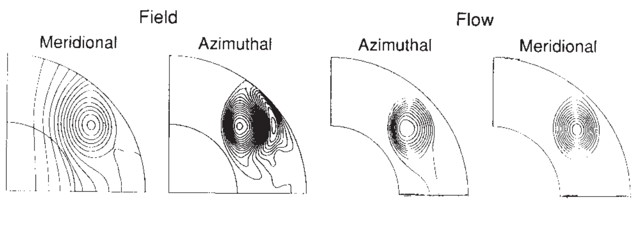

FIG. 3 Contour plots as in Fig. 1, but for an inner- to outer-core radius ratio of 1/2. The phase in the periodic oscillation is approximately at maximum—that is, roughly corresponding to the fourth row of panels in Fig. 1. The larger radius ratio causes the solution to be squeezed more strongly into the outer part of the spherical shell, consistent with the position of the inner-core tangent cylinder. Contour intervals as in Fig. 1.

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the new, reversed state. The difficulty with many previous geodynamo models has been that virtually all fluctuations lead to reversals. This idea that reversals may be triggered by unusually large fluctuations has been proposed before[14,15]; we have provided a more specific mechanism as to how it might function.

Finally, it should be pointed out that if, as widely believed[16,17], a stably stratified layer exists at the core–mantle boundary, that layer would tend to enhance this stabilizing averaging-out process. This could further reconcile the complicated, chaotic nature of the flow and field in the field-generating portion of the outer core with the much more stable nature of the externally observed dipole component of the main field. □

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Recent discoveries of *Dryopithecus* shed new light on evolution of great apes

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THE origin and early evolution of the great ape/human clade (Hominidae) is currently a subject of debate[1–3]. The controversy is fuelled by the fragmentary nature of the fossils which renders it difficult to determine clearly derived features that permit the recognition of fossil members of this clade. We report here the recent discovery of a facial skeleton and a temporal fragment with the petrosal bone of *Dryopithecus laietanus*, which provides a way out of an impasse. The lack of the fossa subarcuata is a great ape and human clade synapomorphy, and proves unequivocally that *Dryopithecus* belongs to this clade. The zygomatic possesses derived characters which reveal that *Dryopithecus* is related to the Ponginae and not to the African apes/humans, as recently suggested[1]. The remaining morphological features are plesiomorphic and thus provide a good model of a common ancestor of all Hominidae.

Dryopithecus is a middle and upper Miocene European hominoid first described from the French locality of St Gaudens in 1856 (ref. 4). The importance of this genus for the comprehension of the origin and evolution of the extant great apes is pertinent to the recent explosion of ideas about its phylogenetic position[1–3]. Many of the arguments, however, have been based solely or primarily on dento-gnathic materials and very incomplete facial remains, which on their own seem to be inadequate for resolving the issues.

During the 1991 excavations at Can Llobateres (northeastern Spain), the type locality of the Vallesian Land Mammal Age, we recovered a series of cranial fragments of *Dryopithecus laietanus*. When reconstructed the fragments comprise the most complete specimen of the genus ever found (Fig. 1). This discovery thus provides a considerably more solid base to approach the problem of the early evolution of the great apes.

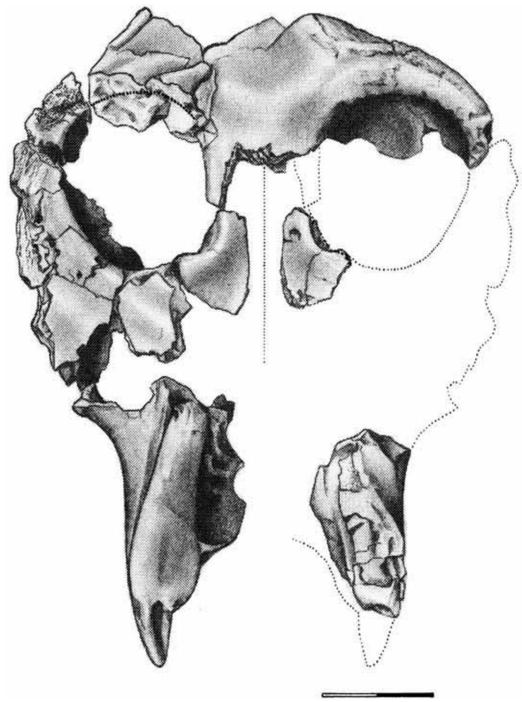

FIG. 1 The partial cranium CLL-18000 includes most of the frontal bone, the greater part of the right zygomatic, the two frontal processes of the maxillae, most of the right maxilla with canine to M^3, the alveolar process of the left maxilla with P^3 to M^3, both the central incisors and a detached portion of the left temporal bone with the petrosal, the external auditory meatus and the mandibular fossa. As reconstructed the cranial fragments show a face which is broad at the orbital level. The orbits are separated by a broad interorbital pillar, are ovoid and slightly higher than wide. The frontal bone is not markedly elevated above the orbits, the zygomatic is strongly developed, broad and anteriorly facing. The alveolar process is high. Scale bar, 2 cm.

The well preserved petrosal bone is the only one known for early hominoids with the exception of *Proconsul*. Like all extant primates apart from the great apes and humans, *Proconsul*[5] has a fossa subarcuata on the endocranial side of the petrosal[6]. In *Dryopithecus* it is absent (Fig. 2) and this is interpreted as a derived feature linking this genus with the clade of extant great apes and humans. Many of the supposed synapomorphies, for a long time used to prove the inclusion of fossil taxa in the great ape clade, were acquired independently as a result of adaptation to environmental circumstances[3,7]. Hence the presence of a synapomorphy found in an independent skeletal element of *Dryopithecus*, the complexity of which makes convergent acquisition of this character unlikely, is of great phylogenetic significance.

Starting from the inference that *Dryopithecus* is a member of the great apes, it can be interpreted further as either primitive with respect to all extant great apes and humans, and thus as the sister group of the latter, or it could pertain either to the clade of the African great apes and humans or to the *Pongo* clade. In the latter case it would have to share at least one apomorphic character with one of the two clades.

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