Numerical dynamo simulations with coupling between inner core, outer core and mantle

Proposal to the Deutsche Forschungsgemeinschaft

1. General Information

Proposal in the priority programme

Geomagnetic variations: spatio-temporal structure, processes and effects on system Earth

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1.2 Title

Numerical dynamo simulations with coupling between inner core, outer core and mantle

1.3 Keyword: dynamo simulation

1.4 Research fields: geophysics, geomagnetism

1.5 Planned research period: Four years.

1.6 Period covered by this proposal: support is requested for 2 years.

1.7 Start of funding period: 01.04.2002

1.8 Summary

Numerical dynamo simulations have captured the principal spatial and temporal properties of the Earth's magnetic field with growing success. We concentrate on three aspects here that should further improve dynamo models. (1) Gravitational coupling between inner core and mantle is perhaps the most effective mechanism for exchanging angular momentum inside the Earth. We plan to incorporte this feature into our 3d dynamo model. This will allow a systematic exploration of inner-core and related mantle rotation. Meaningful comparisons with seismic estimates of inner core rotation rates and decadal changes in length of day will become possible. (2) We recently found dynamos with reversals that resemble those of the geomagnetic field. A detailed study of these models should advance our understanding of reversal mechanisms. Comparisons of simulated properties that would be observable on Earths surface with paleomagnetic records will be an important part of this project. (3) Furthermore, we plan to extend our studies of dynamos with heterogeneous heat flow at the core-mantle boundary to the regime of reversing dynamos. Influences on the reversal frequency and possible preferred paths of the virtual geomagnetic pole (VGP) will be explored.

1.8 Zusammenfassung

Numerische Simulationen des Geodynamos haben die wichtigsten räumlichen und zeitlichen Eigenschaften des Erdmagnetfeldes mit wachsendem Erfolg reproduziert. Wir konzentrieren uns auf drei Aspekte, die helfen sollen, Dynamomodelle weiter zu verbessern: (1) Gravitative Kopplung zwischen innerem Kern und Mantel ist wohl die effektivste Art des Drehimpulsaustausches in der Erde. Wir planen diesen Mechanismus in unser 3D-Modell einzubeziehen. Dies wird erlauben, die Rotation des innerer Kerns und des Mantels systematisch zu untersuchen. Ferner werden sinnvolle Vergeiche mit seismisch abgeschätzten Rotationsraten des inneren Kerns und Dekadenschwankungen in der Tageslänge möglich. (2) Wir fanden unlängst Dynamomodelle mit Polumkehrungen, die denen der Erde ähneln. Eine eingehende Untersuchung diese Modelle soll unser Verständnis des zugrundeliegenden Mechanismus verbessern. Direkte Vergleiche von an der Erdoberfläche beobachtbaren Feldgrößen mit paläomagnetischen Daten werden hier wichtig sein. (3) Weiter planen wir die Untersuchungen von Dynamos mit ungleichförmigen Wärmefluss auf das Regime mit Reversals auftreten. Einflüsse auf die Umpolfrequenz sowie mögliche Vorzugspfade des virtuellen geomagnetischen Pols (VGP) sollen getestet werden.

2. Current status of the research field and applicant's previous contributions

2.1 Current status of the research field

We give a brief overview on contributions by other researchers mainly for those aspects that have not been (fully) addressed in the original proposal.

It has been demonstrated that simple hydrodynamic models of the geodynamo can capture first-order properties of the Earth's magnetic field, such as the dominance of the axial dipole. Numerical dynamo modeling now moves on to: (1) incorporate 2nd-order effects which are nonetheless thought to have significant influence,
(2) explore systematically the influence of control parameters, some of which are far from Earth values,
(3) scrutinize the effect of ad-hoc assumptions like hyperdiffusivities,
(4) compare results from dynamo models with the full spectrum of geomagnetic phenomena and other relevant observations, such as decadal changes in the length of the day.

Gravitational Coupling

Incorporating the exchange of angular momentum between inner core, outer core, and mantle into a numerical dynamo model allows to compute inner core and mantle rotation rates. These results can be compared with seismic estimates of inner core rotation and changes in length of day. The gravitational torque between the mantle and the inner core may be the most effective mechanism for the exchange of angular momentum between mantle and core. Gravitational coupling has initially been proposed by Jault and LeMouël (1989). Buffett (1996) provided a quantitative analysis showing that the gravitational torque can be large.

Mantle heterogeneity causes a perturbation of the gravity potential that departs from azimuthal symmetry. A fixed inner core would deform viscously until its surface coincides with an equipotential surface. If the inner core is rotated out of phase relative to the gravity perturbation by Lorentz or viscous torques, a counteracting gravitational torque develops that may be as large as $10^{21}\,\mathrm{N\,m}$. Simultaneously, the viscous inner core deforms to readjust to the equipotential surface, thus reducing the gravitational torque. Such a strong torque can effectively lock inner core and mantle and therefore inhibit any relative rotation. However, Buffett (1997) distinguishes two viscosity regimes were inner core rotation would still be possible: (1) Large inner core viscosity $\eta > 10^{20}\,\mathrm{Pa\,s}$ where the long viscous relaxation time does not allow the inner core to adjust to the equipotential surfaces, (2) Small inner core viscosity $\eta < 10^{16}\,\mathrm{Pa\,s}$ where the inner core re-adjust to an equilibrium shape so fast that the gravitational torque decays rapidly. The intermediate regime promises to be of more interest, allowing different degrees of inner-core deformation and locking to the mantle. This is the regime we would like to explore.

Buffett and Glatzmaier (2000) published results of a dynamo simulation featuring gravitational coupling at $\eta = 5 \times 10^{16}\,\mathrm{Pa\,s}$. They used a somewhat simplified approach and found that the inner core rotation is reduced to 0.02 deg/yr compared to 0.17 deg/yr in simulations without gravitational coupling. Any meaningful comparison with seismic estimates of inner core rotation rates would therefore demand to include gravitational coupling. But rather than relying on a single simulation it is important to understand the parameter dependence. Buffett and Glatzmaier (2000) report some short runs for different coupling strengths and inner-core viscosities. Our simulations without gravitational coupling have shown that the inner core rotation depends significantly on other system parameters, such as the Ekman number and Rayleigh number (see our report and enclosed manuscript). These dependencies need to be explored further.

Since the gravitational torque exchanges angular momentum between inner core and mantle, changes in the inner core rotation rate thus translate into variations of mantle rotation that can be compared with measured decadal length-of-day changes (Buffett 1999). Buffett and Glatzmaier (2000) show that the amplitude and time dependence have the correct orders of magnitude. But again the parameter dependencies are unclear and need to be explored.

Some other points of their study touch on issues of further interest: No-slip boundary conditions lead to much overrated viscous torques at the Ekman numbers that are numerically feasible. Buffett and Glatzmaier (2000) circumvent this effect by applying stress-free conditions, but only to the azimuthally symmetric velocity components. This somewhat artificial approach eliminates viscous torques on inner core and mantle but avoids the additional numerical complications that stress-free boundary conditions can cause. Inner core rotation rates in Buffett and Glatzmaier (2000) are much smaller than the ones published by Glatzmaier and Roberts (1996). The differences can be attributed to a higher resolution and the fact that Buffett and Glatzmaier (2000) do not employ hyperdiffusivities except for the magnetic field. The last point supports our approach to avoid hyperdiffusivities all together. The strong effect of truncation and hyperdiffusivity on the rotation rates demonstrate that a more careful research is necessary before inner core and mantle rotation rates can be judged with confidence. This is also true for seismological values where newer results suggest that inner-core rotation is much slower than previously anticipated (see Tromp, 2001, for a recent overview).

Stable layering in the core

Convection fills the entire spherical shell of all all 3-D dynamo models published so far. However, there are suggestions that a stably stratified layer may exist at the top of the outer core (e.g. Fearn & Loper, 1981; Braginsky, 1999). Such a layer could form when the heat flow through the core-mantle boundary were subadiabatic, which is a distinct possibility (e.g. Lister & Buffett, 1995). The layer could also consist of accumulated light material set free as the inner core grows. Sarson et al. (1997) studied the influence of a thin stable layer on the dynamo and found it to stabilize the magnetic field. However, they employed a highly truncated so-called 2.5 dimensional model that may not capture the essential physics of core convection, where narrow columnar convection cells are expected. In a stable layer the fluid flow would be almost entirely toroidal (Whaler, 1980). Large differences in the detailed field structure at the CMB are therefore expected between cases where up/downwellings reach the boundary and cases where they are blocked off by a stable layer.

Reversal mechanism

Possible mechanisms for reversals have been discussed for a long time. External causes have been suggested (e.g. Muller & Morris 1986) but generally some internal instability of the dynamo process is held responsible. Is a reversal is a purely magnetic instability, which is the case for reversals observed in kinematic mean-field dynamos (e.g. Olson & Hagee, 1990), or are reversals triggered by changes in the flow pattern? Though some numerical dynamos show reversals of the dipole field (see our enclosed manuscript for an overview), the underlying mechanism remains poorly understood. Glatzmaier & Roberts (1995) reported that the reversed polarity first occurs inside the inner core tangent cylinder and then propagates outward, but later they also observed the inverse behavior (Glatzmaier *et al.*, 1999). Sarson & Jones (1999) conclude from their so-called 2.5-dimensional simulation that buoyancy surges in polar upwellings indirectly cause reversals by affecting meridional circulation. However, although such surges are present in our own models (see enclosed manuscript), they appear to be a side effect rather than a cause for reversals.

Hollerbach & Jones (1993) and Gubbins (1999) suggested that the finite magnetic diffusion time of the inner core plays a key role in preventing too frequent reversal. Again, our own simulations can hardly support this idea (see enclosed). Glatzmaier *et al.* (1999) found that the pattern of heterogenous heat flow at the core mantle boundary has a strong influence on the reversal frequency, which concurs with the notion that slow changes in mantle convection can explain the observed variation of reversal frequency on a 100 Myr time scale. However, most previous models that show reversals have employed hyperdiffusivities. This has been critizised by Grote & Busse (2000), who showed that hyperviscosity can artifically lead to reversing dynamos. Furthermore, the published reversing dynamo models are isolated studies that did not explore the influence of the fundamental control parameters. We conclude that no generally accepted simple explanation of the reversal mechanism is available to date.

Comparison with paleomagnetic data

Dynamo modeling is approaching a state where it becomes possible to compare not only first-order properties of the model field with the geomagnetic field (e.g. axial dipole dominance) but also the detailed spatio-temporal behavior of normal secular variation, excursions, and reversals. Recently Merrill & McFadden (1999) and Dormy *et al.* (2000) reviewed the state of knowledge from paleomagnetism concerning reversals and excursions. According to them, robust observations include: **(1)** The field intensity drops significantly before the reversal and remains low during the transition. There are some hints that the recovery after the directional transition is faster than the previous decrease in intensity. **(2)** The duration of reversals and excursions is in the order of a few thousand years, but the exact timing is uncertain. **(3)** Reversal frequency is a few per million years in the more recent geological past but varies considerably on long time scales (e.g. Cretaceous supercron). Such low frequency modulations are commonly attributed to changes in the lower mantle (e.g. Glatzmaier *et al.* 1999). **(4)** The magnetic field structure during a reversal is probably dominated by higher-order multipoles. **(5)** On time-average, Earth's dipole moment is in the range of $4 - 6 \times 10^{22} Am^2$, slightly less than the present dipole moment.
Dormy *et al.* (2000) suggest that dynamo models, which are claimed to be "Earth-like", should be tested against such observations. Past reversing dynamo models compared with single aspects rather than with the full spectrum. Also, model run times have been to short for a meaningful statistics, for example on reversal frequencies.

In paleomagnetism the details of the directional change is commonly described in terms of virtual geomagnetic pole paths (VGPs). The question whether VGPs follow bands of preferred longitudes is a matter of debate for several years now and has not been settled. If these bands exist, they must reflect an influence of lateral lower-mantle inhomogeneities. The same is true for the claimed clustering of VGPs in certain regions away from the rotation poles (Hoffman 1996). On open question concerns the significance of VGPs, obtained from observations at specific sites at the Earth's surface, when the magnetic field is not dominated by the dipole component. Using a simple kinematic dynamo model, Gubbins & Sarson (1994) showed that VGP paths derived for different sites may fall into narrow bands even though the transitional magnetic field is not dipole-dominated. However, it is not clear if the same could hold for hydrodynamic dynamo models with a more complex field geometry.

Another question is whether these are differences on a global scale in the amplitude of "normal" secular variation, i.e. excluding times of reversals and excursions. In the historical field secular variation in the Pacific is lower than elsewhere (Bloxham & Gubbins 1985). From the dispersion of paleomagnetic directions on Hawaii it has been concluded that this has persisted over a geologically long period (e.g. McWilliams *et al.* 1982), however, others (e.g. McElhinny *et al.* 1996) see no evidence for this so-called "Pacific dipole window". If systematic differences in the secular variation exist, they must have their origin in the coupling to the mantle. This could occur either through a high but laterally heterogeneous lower mantle conductivity, or through thermal coupling. It has not been tested in 3-D dynamo models whether either type of coupling can lead to differences in secular variation on a global scale.

2.2 Previous work of applicants

Enclosed is a separate progress report for the past 18 months. It also covers work done under separate grant Ch77/10. We also enclose four manuscripts (submitted or accepted for publication in refereed journals) that describe in detail the results of our work.

3. Scientific aims and work schedule

3.1 Scientific aims

We aim at clarifying the influence of thermal boundary conditions and electromagnetic and gravitational coupling of inner core, outer core, and mantle on the geodynamo. The main focus will be on polarity reversals, their causes, their spatial and temporal character, and the kind of signal they leave in paleomagnetic data. We will explore these aspects more systematically than previously. For this purpose we use self-consistent 3D dynamo simulations that do not employ parameterizations such as hyperviscosities. We aim at a range of control parameters that are, in some respects, still remote from Earth's core values, but nevertheless give rise to magnetic fields that agree in intensity, spatial pattern, and time scales with what is known about the geomagnetic field. This will help to make geodynamo simulations more realistic and turn them into a tool for interpreting paleomagnetic data.

In particular, we want to address the following questions:

• How do the rotation rates of the gravitationally coupled inner core and mantle depend on the fundamental control parameters (Rayleigh number, Ekman number) and on inner-core viscosity?

• Do the resulting changes of the mantle rotation rate resemble observed length-of-day changes ?

• How do different thermal boundary conditions control the time-dependence of the magnetic field? Are there persistent regions of low secular variation at the Earth's surface ?

• How important are heat flow variations at the core mantle boundary given that the geodynamo may largely be driven by compositional buoyancy ?

• Is a stably stratified layer near the core-mantle boundary dynamically possible, in particular if the mean heat flow from the compositionally convecting core is subadiabatic ? Would it have a strong influence on the structure and time-dependence of the magnetic field ?

• Can dynamo models with polarity reversals provide a clue for the fundamental mechanism of reversals (if there is such thing) ? Are they triggered by changes in the flow structure ? Is the decrease in dipole strength before the directional change a prerequisite or part of the reversal itself ?

• How well do simulated reversals agree with actual geomagnetic reversals in terms of time-scales, field structure and field intensity during the reversal ?

• Is there an important difference between excursions and reversals?

• What is the significance of virtual geomagnetic dipole paths (VGPs), taken at different sites at the Earth's surface, given that the magnetic field is largely non-dipolar during a reversal ?

• How is the reversal frequency affected by magnitude and pattern of the imposed heat flow distribution?

• Does thermal core-mantle coupling lead to preferred virtual dipole paths during reversals ? Can it explain the clustering of VGPs at intermediate positions?

• How does this all tie up with lower mantle thermal structures inferred from seismological data?

3.2 Work Schedule

3.2.1 GRAVITATIONAL COUPLING

The (first order) gravity potential in the core follows lateral inhomogeneities of mantle density and mantle figure and is thus not spherically symmetric. Of special interest are the small deviations from azimuthal symmetry, which can be estimated from the geoid or from seismic models. Global variations are commonly described in terms of spherical harmonics $Y_{\ell m}(\theta, \phi)$ of degree ℓ and order m. The term ($\ell = m = 2$) is dominant for lower mantle variations and we concentrate on this harmonic.

Without inner core rotation, the inner core surface would viscously deform until adjusted to an equipotential surface (hydrostatic equilibrium). The inner core radius can thus also be expressed in spherical surface harmonics:

$$r_{ICB} = r_0 + r_{\ell m} Y_{\ell m}(\theta, \phi)$$

here r_0 is the spherical symmetric part and $r_{\ell m}$ the amplitude of the small deviations ($r_{\ell m} \ll r_0$).

We use a simplified equation to compute the evolution of the inner-core surface with time (Buffett 1997):

$$\frac{\partial r_{\ell m}}{\partial t} = \frac{r'_{\ell m} - r_{\ell m}}{\tau_\ell} - im\,(\omega_i - \omega_m)\, r_{\ell m}$$

Here, $r'_{\ell m}$ is the deformation at hydrostatic equilibrium, and ω_i and ω_m are the inner-core and mantle rotation rates respectively. Note that $r'_{\ell m}$ as well as $r_{\ell m}$ are complex. The inner-core viscous relaxation time τ_l is proportional to the inner-core dynamic viscosity (Buffett 1997).

Any inner-core rotation ω_i moves equipotential surface and inner-core boundary modulation out of phase. This results in a deformation of the inner core on time scale τ_ℓ. In addition, a gravitational torque Γ_g is invoked, which tries to bring inner core and mantle back into phase:

$$\Gamma_g = \Gamma'_g \; |r_{\ell m}| \; sin(m\varphi)$$

where Γ'_g is a measure for the strength of the gravitational torque and φ is the phase between mantle and inner-core deformation. The parameter Γ'_g contains mantle and inner-core parameters that are constant in time (Buffett 1997). We do only allow for inner-core rotations about the z-axis and consequently calculate only the z-components of the torques. The two remaining components of the gravitational torque are several orders of magnitude larger and therefore effectively align inner-core and mantle rotation axis. According to Bruce Buffett, the amplitude of the gravitational torque lies in the range $\Gamma'_g = 10^{20} - 10^{21}\,\mathrm{N\,m}$, depending on the employed mantle model.

The following steps are planned to explore inner-core and mantle rotation:
(1) Implementation of the relevant equations. The inner core deformation will have to be time stepped as part of our equation system that describes the dynamo process. Because of its smallness, any influence of the deformation on the fluid flow in the outer core is neglected. The gravitational torque must be coded into the angular momentum equations for inner core and mantle. **(2)** Exploring the dependence of inner core and mantle rotation on τ and Γ'_g. These parameters are poorly known. We will thus cover

several possible combinations. Of special interest will be the cases of intermediate viscous relaxation times ($\tau \approx 1\,\mathrm{yr}$) and not too large Γ'_g, where gravitational coupling still allows for inner-core rotation but determines the upper bounds of the rotation rate. Three to four different viscous relaxation times (small, intermediate, longer) and two values of the coupling strength ($\Gamma'_g = 10^{20}, 10^{21}\,\mathrm{N\,m}$) seem desirable. **(3)** Testing at which parameters an initially spherical inner core will deform. This will depend on the viscous relaxation time and inner-core rotation rates. If the inner core rotates too fast or the relaxation time is too long inner-core deformations will have no time to grow significantly. However, once a small deformation has developed, gravitational coupling may slow down inner core rotation and therefore support further growth of $|r_{\ell m}|$. Whether this run-away process starts depends on inner-core viscosity, Lorentz torque, and viscous torque. **(4)** Exploring the dependence on Ekman and Rayleigh number. Glatzmaier and Roberts (1996) report that the rotation is driven by thermal winds associated with plumes rising above the poles of the inner core. The inner core couples magnetically to these winds. Analytical analysis shows that thermal winds scale with the Rayleigh number. However, the parameter dependence of the inner-core rotation is likely to be more complex: The structure of the rising plumes and the thermal wind is increasingly complicated at larger Rayleigh numbers. The magnetic coupling may therefore become less effective. We are thinking of using at least two Ekman numbers ($E = 3\times10^{-4}$, $E = 10^{-4}$) and two Rayleigh numbers. **(5)** Comparing results for stress free and rigid boundary conditions. Contrary to the ad-hoc approach of Buffett and Glatzmaier (2000), who assume stress-free conditions only on the solid body rotation part of the flow, we would like to run completely stress-free simulations. This would eliminate the viscous torque on inner core and mantle.

3.2.2 CHARACTERISATION OF REVERSALS

The magnetic reversals found in by us previously in dynamo models with sufficiently high Rayleigh number (Kutzner & Christensen 2001; Wicht 2001 [enclosed]) will serve as a starting point for (1) a more in-depth study of the phenomenology of simulated reversals and (2) for an attempt to develop an understanding of the reversal mechanism described in the next section.

In order to study time-dependent aspects of our dynamo models in general, and reversals in particular, we plan to take records of the Gauss coefficients every few time steps from all our future model runs. The records will then be used to calculate, for points at the Earth's surface, observable magnetic elements (inclination, declination, intensity) or derived properties such as virtual geomagnetic pole positions. Because the emphasis is on properties of the magnetic field that could be observed at the surface, we restrict this to the low-order coefficients, for example up to $\ell = m = 8$. This is a strong data compression compared to the full resolution used in the model (typically up to

$\ell = m = 85$), which enables us to keep a quasi-continuous record. These records will enable us to calculate any desired property of the surface magnetic field a-posteriori.

One application will be the calculation of VGPs for different hypothetical sites at the Earth's surface. Aside from a general characterization and comparison of the VGP paths with observations, we want to clarify whether the VGP paths calculated for different sites fall into bands even when higher multipoles dominate during a reversal, and if so, what properties in the spatial and temporal structure of the magnetic field are the cause for it. We will first use models with simple boundary condition that do not break the azimuthal symmetry; therefore we do not expect the same preferred reversal paths for different reversals. However, this study will also prepare the ground for the calculations with heterogeneous heat flow conditions at the core mantle boundary (section 3.2.4).

We plan to continue the statistical analysis of reversing dynamos in terms of polarity interval length (Wicht 2001) and want to accompany this by an analysis of reversal duration. We will base this analysis on virtual dipole locations for individual observing sites rather than on the true dipole direction of the dynamo model, which we used so far, but which cannot be determined from paleomagnetic records. The result may be quite different; Merrill & McElhinny (1999) point out that "At such times [i.e., when the dipole intensity is low with respect to the non-dipole field] it would be possible for the dipole field to change sign, perhaps many times, without that being detectable in the paleomagnetic data." It will be interesting to learn if this leads to significant differences in the statistics of intermediate directions or reversal frequency. So far even our most "Earth-like" models exhibit sometimes periods with many short polarity intervals (or erratic fluctuations of the dipole) which do not seem to exist in this form for the Earth. Other models can be completely dominated by this kind of behavior. While we found that "Earth-like" behavior is favored by chemically rather than thermally driven convection and occurs in a narrow band of Rayleigh numbers, the influence of other parameters on reversal frequency and duration has not been explored. We want to investigate for the case of chemical convection the influence of the Ekman number, in particular towards lower (more realistic) values. Because the necessary resolution increases upon reducing the Ekman number and because a meaningful statistics requires a long time series, this will be restricted to two or three cases at an Ekman number of 10^{-4} compared to 3×10^{-4} in our previous preferred model (Kutzner & Christensen 2001). The influence of the magnetic Prandtl number on reversals will also be studied.

3.2.3 REVERSAL MECHANISM

Several further examinations will be necessary to clarify the reversal mechanisms. So far, we have concentrated on the related field evolution at the core-mantle boundary.

But the processes inside the core are essential for understanding the underlying mechanisms. Of special interest is the correlation of flow field and magnetic field during the reversal. Several reversals must be analyzed in order to identify common features. A correlation that is observed only once might just be a coincidence. It has been proposed that buoyancy surges inside the tangent cylinder and the associated decrease in meridional circulation might favor field reversals (Sarson & Jones, 1999). We plan to explore the region inside the tangent cylinder more closely and will in particular look for correlations between periods of increased outward heat flow, meridional circulation, and field reversals.

Another interesting issue is the question where the field reversal starts inside the core: at the core-mantel boundary or more towards the inner-core? The tangent cylinder may again play a special role here. Related is the question whether poloidal and toroidal field reverse at the same time starting at the same location? We plan way to address these questions by examining the evolution of the large scale field at different depths of outer and inner core.

A further line of approach is to more closely explore the magnetic flux patches, whose sum forms the large scale field. We often see these patches appearing at low latitudes and then migrating poleward. Other flux spots pop up at higher latitudes, apparently due to flux expulsion. This suggests two possible reversal scenarios: either sufficient inverse flux patches migrating towards the pole or increased expulsion of inverse field. Further research is needed to decide this alternative. More related questions: Are the migrating flux patches advected or is this a phase propagation, i.e. a dynamo wave? Do the patches have deeper roots below the core-mantle boundary?

To compliment the difficult analysis of the small scale simulations, we would like to return to much more moderate parameters, where simple dipole fields with oscillatory reversals or chaotic fluctuations in dipole direction can be found (Kida *et al.*; Kida & Kitauchi, 1998). Since the Rayleigh number is only marginally critical in these models, their time dependence as well as their flow and magnetic field structures are much simpler and less chaotic. This will hopefully allow to fully analyze and understand these simple reversals and may give hints for possible mechanism at more Earth-like parameters.

3.2.4 THERMAL CORE-MANTLE COUPLING

A heterogeneous thermal boundary condition at the core-mantle boundary influences thermal convection in the core, but not the chemical convection part. For a realistic assessment of the influence of thermal core-mantle coupling both sources of buoyancy must be taken into account properly. So far, we considered several end-members of thermally or compositionally driven convection. In future models, we want to use a unifying description of combined thermal and compositional convection. Based on the assumption that the effective (turbulent) diffusivities for heat and composition are the same, we combine temperature T and concentration C into a single *buoyancy variable* X:

$$X = \Delta\rho C + \rho\alpha T$$

for which the usual advection-diffusion equation holds ($\Delta\rho$ is the compositional density contrast and α the thermal expansivity). Interpreting T and C as the deviations from a reference state (adiabatic in case of temperature) which undergoes secular drift, the effects of outer core cooling, secular enrichment of light element, and of the adiabatic gradient can be expressed as an effective volumetric sink term for X. At the inner-core boundary, the release of light constituent and of the latent heat of inner-core freezing, which are both controlled by the total heat loss through the core-mantle boundary (Lister & Buffed 1995), contribute to a flux boundary condition for X. At the core-mantle boundary the flux of light constituent is zero, and only the thermal flux imposed by the mantle contributes to the condition for $\partial X/\partial r$ as a function of the angular variables. In this way all important effects that influence thermal and chemical buoyancy can be accounted for within the framework of a simple Boussinesq description. All the details of this approach have been worked out theoretically and the dynamo code is ready to incorporate it.

In a first step we will re-investigate one or two dynamo models in the non-reversing regime with imposed heterogeneous boundary heat flow described by a simple spherical harmonic pattern. We had used these models to determine the influence of thermal coupling on the structure of the time average magnetic field (Olson & Christensen 2001), but assumed pure thermal convection. We expect that for combined thermo-chemical convection the variations of boundary heat flow must become larger to have a similar effect. An interesting question is whether the dynamo can still work when the (superadiabatic) heat flow becomes negative on a significant part of the core-mantle boundary – in our previous calculations the dynamo failed under these circumstances. Another point of interest with the combined model is whether there is a difference between cases of positive mean heat flow and the singular case of zero net (superadiabatic) heat flow.

In the next step, we will proceed to the regime where dipole reversals occur. Starting point is a model of pure chemical convection described in Kutzner & Christensen (2001), that is, a case with zero superadiabatic boundary heat flow. We will test models with different amplitudes of heat flow heterogeneity (keeping the net heat flow at zero), and start with a spherical harmonic degree and order two pattern (Y22-pattern) which is dominant in lower mantle seismic tomography models. Depending on results we will later study different harmonic pattern, such as Y10, which leads to a significant axial magnetic quadrupole contribution. It may or may not reverse along with the dipole. As a final step we would study a pattern of heat flow heterogeneity derived from mantle tomography. Because these calculations are very time-consuming, a systematic exploration of parameter space is hardly possible. However, we would aim at testing the robustness of results by varying the most important control parameters (Ekman number, magnetic Prandtl number) at least in one case study each.

An obvious point of interest with these models is the influence of heterogeneous boundary heat flow on the frequency and other characteristic properties (duration, field intensity) of reversals. We will calculate VPG paths, as they would be recorded at different sites at the Earth's surface and do a statistical analysis with regard to the possible existence of preferred longitude bands or clustering of VGPs in certain regions.

3.2.5 THERMAL COUPLING AND SECULAR VARIATION

A somewhat separate point is the calculation of global differences in secular variation during periods of stable dipole polarity. We will use the continuous records of low-degree and order spherical harmonic coefficients of suitable dynamo model runs and calculate directional data (declination and inclination) for a large number of sites at the Earth's surface. One point of interest is the comparison with typical secular variation curves from historical and archeomagnetic data in terms of time-scales, amplitudes and the overall pattern. For each site long-term statistical properties (mean and variances of declination and inclination) will be calculated and will be compared between different sites. When systematic differences exists, it will be interesting to determine their relation to the imposed heat flux pattern at the core mantle boundary.

3.2.6 STABLE STRATIFICATION NEAR THE OUTER BOUNDARY

To assess the possible formation of a stably stratified layer at the outer boundary and its influence on the geodynamo, we plan two different kinds of model studies. The first one uses the approach described in section 3.2.4 and sets the flux condition $\partial X/\partial r$ on the outer boundary to a positive value, representing a subadiabatic heat flow. In addition to thermal stability near the outer boundary, the light compositional constituent may dynamically accumulate and enhance the stable stratification. One point of interest is to determine if a stable layer will indeed form, or if it is likely to be disrupted by constraints due to Coriolis forces (Proudman-Taylor) or by electromagnetic forces. Zhang & Schubert (1996) found that columnar convection can easily penetrate into a convectively stable layer (and would tend to destroy it), however, their calculation was only for the marginal stability limit. To quantify dynamic stability, we would monitor the variation of toroidal and poloidal flow components as a function of radius.

The development of a highly stable compositional layer may be prevented in our model because for numerical reasons the diffusivity is much larger than realistic (even turbulent) values. If a significant stable layer does not develop naturally, we will in a second series of models enforce a stable layer by superimposing a highly stable non-diffusive compositional gradient near the outer boundary, such that only toroidal flow will be possible in this layer. The influence on the dynamo process in general and on the structure of the magnetic field on the outer boundary will be studied.

3.2.7 TECHNICAL ASPECTS AND TIME TABLE

The available parallel computer (IBM SP2 with 7 four-processor nodes and one 16-processor node at our exclusive disposal) is ideally suited for running the large number of case studies needed for a systematic study. The code is run very efficiently in a shared-memory parallel mode (using OpenMP directives), with a speedup factor of 3.7 on a four-processor node and about 13 on a 16-processor node. Because we can keep the machine busy by running a sufficient number of different cases in parallel, we did not attempt so far to parallelize the code on the multi-node level with message-passing directives.

Some of these model runs will be done on a routine basis, and we ask for money to support assisting students (*Studentische Hilfskräfte*) who will supervise these runs, do a preliminary evaluation of the results, prepare graphical presentations and perform other routine work.

Johannes Wicht will implement the necessary modification to the code to treat gravitational coupling before the start of the next funding period, provided a separate grant request (CH77/10-2) for support covering the time 1.1.2002-31.3.2002 will be funded. In the first year covered by this proposal he will study gravitational coupling as described in section 3.2.1. He will also start to work on some aspects described in section 3.2.2 (characterization of reversals). Whether Dr. Wicht will continue in this project in the second year is not clear at this time and depends on his plans concerning professional life and German legal rules concerning temporary employment. In the second year he or a new postdoc will concentrate on the reversal mechanism (3.2.3), and may also be involved in either topic 3.2.5 or 3.2.6.

Carsten Kutzner will begin to work on the influence of thermal coupling on reversals (3.2.4) before the beginning of the funding period and is expected to finish it within its first year. He will closely collaborate with JW on 3.2.2. We expect him to complete his PhD thesis by March 2003. In the second year of the funding period a new PhD student would start with either 3.2.5 (thermal coupling and secular variation) or 3.2.6 (stable layering in the core). Neither project requires more than minimal technical changes to the dynamo code and is suitable for a beginner.

Bibliography

Braginsky, S.I., Dynamics of the stably stratified ocean at the top of the core, *Phys. Earth Planet. Int.*, **111**, 21-34.

Buffett, B.A., Geodynamic estimates of the viscosity of the Earth's inner core, *Nature*, **388**, 571-573, 1997.

Buffett, B.A., A mechanism for decade fluctuation in the length of day, *Geophys. Res. Lett.*, **23**, 3083-3806, 1996.

Buffett, B.A. and Creager, K.C., A comparison of geodetic and seismic estimates of inner-core rotation, *Geophys. Res. Lett.*, **26**, 1509-1512, 1999.

Buffett, B.A. and Glatzmaier, G.A., Gravitational Braking of inner-core rotation in geodynamo simulations, *Geophys. Res. Lett.*, **27** 3125-3128, 2000.

Coe, R.S., Hongre, L., and Glatzmaier, G.A., An examination of simulated geomagnetic reversals from a paleomagnetic perspective, *Phil. Trans. R. Soc. London. A*, **358** 1141-1170, 2000.

Fearn, D.R. and Loper, D.E., Compositional convection and stratification of the Earth's core, *Nature*, **289** 393-394, 1981.

Glatzmaier, G.A., Coe, R.S., Hongre, L., and Roberts, P.H., The role of the Earth's mantle in controlling the frequency of geomagnetic reversals, *Nature*, **401** 885-890, 1999.

Glatzmaier, G.A. and Roberts, P.H., Rotation and magnetism of the Earth's inner core, *Science*, **274**, 1887-1891, 1996.

Grote, E., Busse, F.H., and Tilgner, A., Effects of hyperdiffusivities on dynamo simulations, *Geophys. Res. Lett.*, **27** 2001-2004, 2000.

Gubbins, D. and Sarson, G., Geomagnetic field morphologies from a kinematic dynamo model, *Nature*, **368** 51-55, 1994.

Hoffman, K., Transitional paleomagnetic field behavior: Preferred paths or patches?, *Surv. Geophys.*, **17** 207-211, 1996.

Jault, D. and LeMouël, J.-L., The topographic torque associated with tangentially geostrophic motion at the core surface and inferences in the flow inside the core, *Geophys. Astrophys. Fluid Dyn.*, **48**, 107-120, 1989.

Kageyama, A., Ochi, M.M., and Sato, T., Flip-flop transitions of the magnetic intensity and polarity reversals in the magnetohydrodynamic dynamo, *Geophys. Rev. Lett.*, **82**, No 26, 5409-5412, 1999.

Kida, S., Araki, K. and Kitauchi, H., Periodic reversals of magnetic field generated by thermal convection in a rotating spherical shell, *J. Phys. Soc. Jap.*, **66**, 2194-2201, 1997.

Kida, S. and Kitauchi, H., Thermally driven MHD dynamo in a rotating spherical shell, *Prog. Theoret. Phys. Suppl.*, **130**, 121-136, 1998.

Kutzner, C. and Christensen, U., ¿From stable towards reversing numerical dynamos, *submitted to Phys. Earth Planet. Int.*, 2001.

Lister, J.R. and Buffett, B.A., The strength and efficiency of thermal and compositional convection in the Earth's core, *Phys. Earth Planet. Inter.*, **91**, 17-30, 1995.

McElhinny, M.W., McFadden, P.L. and Merrill, R.T., The myth of the Pacific dipole window, *Earth Planet. Sci. Lett.*, **143**, 13-22, 1996.

Merrill, R.T. and McFadden, P.L., Geomagnetic polarity transitions, *Rev. Geophys.*, **37**, 201-226, 1999.

McWilliams, M.O., Holcomb, R.T. and Champion, D.E., Geomagnetic secular variation from ^{14}C dated lava flows on Hawaii and the question of the Pacific non-dipole low, *Phil. Trans. Roy. Soc. London*, A **306**, 211-222, 1982.

Muller, R.A. and Morris, D.E., Geomagnetic reversals from impacts of the Earth, *Geophys. Res. Lett.*, **13**, 1177-1180, 1986.

Olson, P. and Hagee, V.L., Geomagnetic polarity reversals, transition field structure and convection in the outer core, *J. Geophys. Res.*, **95**, 4609-4620, 1990.

Sarson, G.R., Jones, C.A. and Longbottom, A.W., The influence of boundary region heterogeneity on the geodynamo, *Phys. Earth Planet. Inter.*, **101**, 13-32, 1998.

Sarson, G.R. and Jones, C.A., A convection driven geodynamo reversal model, *Phys. Earth Planet. Inter.*, **111**, 3-20, 1999.

Tromp, J., Inner-core anisotropy and rotation, *Annu. Rev. Earth Planet. Sci.*, **29**, 47-69, 2001.

Whaler, K.A., Does the whole of the Earth's core convect?, *Nature*, **287**, 528-530, 1980.

Wicht, J., Inner-core conductivity in numerical dynamo simulations, *submitted to Phys. Earth Planet. Int.*, 2002.

Zhang, K. and Schubert, G., Penetrative convection and zonal flow on Jupiter, *Science*, **273**, 941-943, 1996.

4. Requested resources

4.1 Personal

1x BAT IIa for 2 years (Postdocs: Dr. Johannes Wicht first year, NN or Wicht 2nd year)

1x BAT IIa/2 for 2 years (PhD students: Carsten Kutzner first year, NN 2nd year)

Assisting students' salaries (*Studentische Hilfskräfte*) 30 hours monthly for 2 years

4.2 Instruments: none

4.3 Consumables

Computer consumables (CDs, color prints, etc.)	1000 €

4.4 Travel

Cooperation with Prof. Peter Olson, Johns Hopkins University, Baltimore	
1 person flight & train 800 €, 15 per-diems at 154 €	3110 €
SEDI conference Lake Tahoe (USA) 7/2002:	
1 person flight & train 800 €, 7 per-diems at 154 €, conference fee 180 €	2058 €
AGU conference in San Francisco (USA) 12/2002:	
1 person train & flight 800 €, 7 per-diems at 175 €, conference fee 180 €	2205 €
EGS conference Nice (France) 4/2003:	
1 person flight & train 500 €, 5 per-diems at 86 €, conference fee 175 €	1105 €
IUGG / IAGA assembly Sapporo (Japan) 8/2003:	
1 person flight & train 1000 €, 10 per-diems at 180 €, conference fee 200 €	2000 €
Total costs of travel:	10478 €

5. Prerequisites for proposed scientific studies

5.1 Research team

Prof. Dr. Ulrich Christensen
Dr. Johannes Wicht / NN (salary requested here)
Carsten Kutzner / NN (salary requested here)
Ulrich Einecke, system administrator (support in programming and visualization)

5.2 Cooperation with other groups

Prof. Dr. Peter Olson, Johns Hopkins University, Baltimore, USA

Our collaboration will continue for the duration of this proposal, in particular on thermal core-mantle interactions.

Prof. Dr. A. Tilgner, Institut für Geophysik, Universität Göttingen
Prof. Tilgner works on related problems and we are regularly discuss results.

Dr. E. Schnepp, Geophysik, Universität Göttingen
Dr. Schnepp is working on paleomagnetic problems and is an associate member of the applicant's group. She will consult concerning the comparison with observational data.

5.3 International context: Collaborations as detailed in 5.2.

5.4 In-house equipment

We have exclusive access to a parallel computer IBM SP2 with 'Winterhawk II'-nodes (7 nodes with 4 processors each and one node with 16 processors), each node with 3 GByte of shared memory.

5.5 Running costs carried by the institute: about 1500 DM / year

5.6 Other requirements: none

6. Declarations

6.1 Application to other grant agencies

This proposal has not been submitted to any other grant agency or any other programme. We will inform the DFG immediately in case we apply elsewhere for support for this proposal.

6.2 University DFG spokesman: The spokesman at the university Göttingen, Prof. Dr. Hardeland, has been informed about the proposal.

7. Signatures

Göttingen, 24.10.2001

(Ulrich Christensen)

8. Enclosures:

1) CV, Ulrich Christensen

2) Publication list 1996-2001, Ulrich Christensen

3) Publication list, Johannes Wicht 4) Progress Report 1999 - 2001

5) 4 manuscripts resulting from this project