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The Geodynamo:
Models and Supporting Experiments

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The Geodynamo: Models and Supporting Experiments

Abstract

The magnetic field is a characteristic feature of our planet Earth. It shelters the biosphere against particle radiation from the space and offers by its direction orientation to creatures. The question about its origin has challenged scientists to find sound explanations. Major progress has been achieved during the last two decades in developing dynamo models and performing corroborating laboratory experiments to explain convincingly the principle of the Earth magnetic field.

The article reports some significant steps towards our present understanding of this subject and outlines in particular relevant experiments, which either substantiate crucial elements of self-excitation of magnetic fields or demonstrate dynamo action completely. The authors are aware that they have not addressed all aspects of geomagnetic studies; rather, they have selected the material from the huge amount of literature such as to motivate the recently growing interest in experimental dynamo research.

Der Geodynamo: Modellvorstellungen und Experimente

Zusammenfassung

Das magnetische Feld ist eine charakteristische Eigenschaft unserer Erde. Es schützt die Biosphäre gegen Partikelstrahlung aus dem Weltraum und bietet den Lebewesen Orientierung durch seine Ausrichtung. Die Erklärung seines Ursprungs ist für Wissenschaftler stets eine Herausforderung gewesen. Größere Fortschritte wurden während der letzten zwei Jahrzehnte bei der Entwicklung theoretischer Modelle zur Entstehung des Geomagnetismus und bei der Planung und Durchführung von Laborexperimenten erzielt, die diese Vorstellungen unterstützen.

Der Bericht zeigt einige wichtige Schritte auf dem Weg zum gegenwärtigen Verständnis des Geomagnetismus auf und hebt dabei in der Darstellung Experimente heraus, die entweder wichtige Elemente der Selbsterregung magnetischer Felder oder aber den Dynamo-Effekt selbst demonstrieren. Die Autoren sind sich bewusst, dass sie dabei nicht alle Aspekte der in der Literatur aufgeführten Untersuchungen zum Geomagnetismus ansprechen. Sie haben vielmehr die Auswahl so getroffen, dass die gegenwärtig stark expandierenden experimentellen Aktivitäten zur Dynamoforschung zur Geltung kommen und motiviert werden.

Contents

1. Introduction

1.1 Some Properties of the Earth's Magnetic Field

William Gilbert, physician of Queen Elizabeth I of England, in his book „De Magnete“ in the year 1600, first published a systematic investigation of the Earth’s magnetic field. From his own experimental observations and from measurements taken by mariners of the English navy he concludes that the Earth behaves like a bar magnet with two magnetic poles located near the geographic North- and South pole.

Repeated measurements on the Earth's surface and more recently by satellites from space have shown that the magnetic field has a dipole structure by 90% while the other 10% are completed by higher order poles. Based on these measurements and on magneto-potential theory isographs of the terrestrial magnetic field have been developed by several authors among others by Bloxham & Gubbins (1985) and recently by Jackson et al. (2000) and Haak (2001) (cf. Figure 1.1). Its mean intensity amounts to about 0.4 Gauss at the surface varying locally and in the short term (10 to several 100 years) by up to 5% percent. The movement of the magnetic North Pole by several hundred kilometers to the northwest during the last 170 years is an obvious indicator for this. Moreover, reliable measurements recorded for the last 400 years have shown that local variations of the field drift westwards at a rate of 0.2 degrees per year and the field intensity weakens by about 0.07% per year (cf. Courtillot & Le Mouel (1988)).

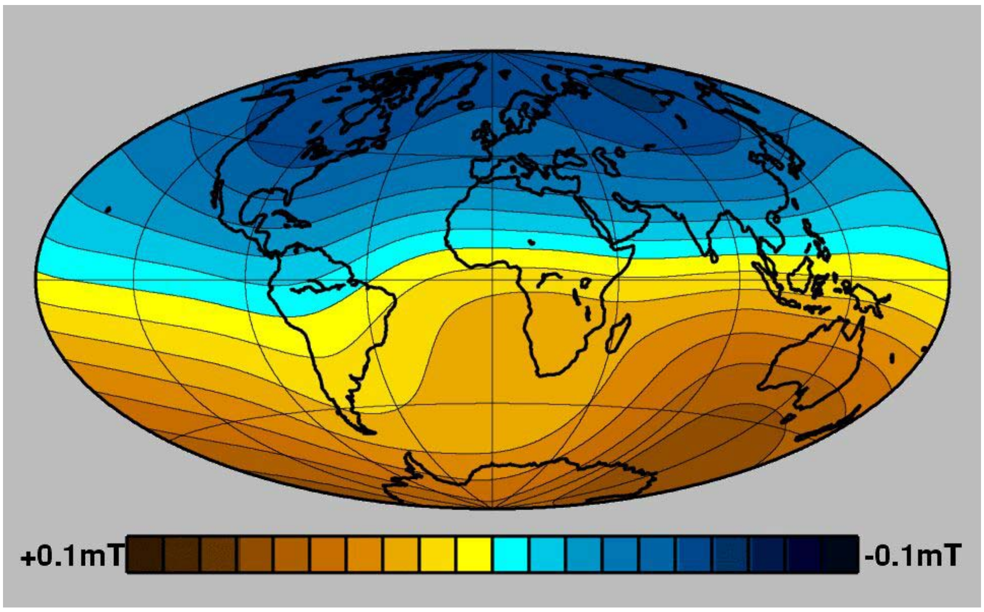

Figure 1.1. Isolines of the radial component of the Earth's magnetic field at the Earth's surface after Haak (2001).

Significant variations of the field have also been identified on time scales of thousands and millions of years. There is a striking observation from paleomagnetic measurements utilizing the remanent magnetism in geological formations. Since the Earth's magnetic field turned up first about 3.5 Billion years ago it has changed its polarity very many times, during the last 150 Million years in the average every $2 \cdot 10^5$ years. The transition between different polarities occurred much faster in periods of several thousand years (see Merrill et al. 1996). Moreover, during the transition period the magnetic field intensity weakened significantly down to only 10% of its normal value. These randomly occurring events are called reversals.

Earlier speculations that the Earth's magnetic field is caused by a permanent ferromagnet in the Earth's interior had to be rejected, as the temperatures in the Earth's core are far beyond the Curie temperature of about 800 °C, which is the upper thermodynamic limit for ferromagnetism. Another consideration to explain its origin by a freezing in of a magnetic field, originating from external cosmic sources during the early formation process of the planet, had to be abandoned also, as such a field would decay within a period of about 10^5 years according to the electrical conductivity of the Earth's liquid core and its outer radius.

Lamor (1919) gave the first sound explanation of the evidently dynamic behaviour of the Earth's magnetic field. He proposed that the magnetic field of sun spots, which had been observed and measured by astrophysicists, could be generated electrodynamically by the motion of conducting fluids in the sun's interior, and he speculated that an "Earth's magnetic field would require fluidity and residual circulation in deep-seated core regions". Thus, he inferred the stellar magnetic fields from dynamo action. Geophysicists later adopted this hypothesis as the only possible origin of geomagnetism. Elsasser (1946) and Bullard (1949) developed first physical models based on relative motions in the Earth's core.

Here we recall that dynamos are systems that are capable to convert mechanical into electromagnetic energy. Technical dynamos for electricity generation are constructed in a complex manner employing multi-connected wiring arranged in several copper coils combined with ferromagnetic material in relative rotation to each other. They contrast with dynamos in the interior of stars or planets that should exist in a singly connected domain of a homogeneous, electrically conducting and moving fluid. They are named Homogeneous Dynamos. Their existence is not clear a priori, as any electric current may short circuit and vanish from the interior of the fluid body. We address these questions in the following sections giving particular emphasis to the rapidly developing experimental investigations.

1.2 Structures of the Earth's Interior

Based on general thermodynamic estimates and on precise seismic measurements a quite detailed picture of the internal structure of the Earth is available. From a heat balance at the surface and derived density stratification data in the interior the pressure and temperature distribution can be concluded. There is a temperature of about 6300 °C, a pressure of 3.6 Million bar and a density of $1.3 \cdot 10^4$ kg/m^3 in the center. The structure of the Earth's interior can be inferred from the total mass, the internal density distribution, the system of chemical elements and the measured propagation speed of seismic waves in the core. The Earth has a solid metallic inner core with a radius of about 1200 km consisting mainly of iron and nickel. The solid core is surrounded by a liquid outer core, a spherical shell containing an iron-nickel alloy with an admixture of 10 % by weight of lighter elements such as oxygen, sulfur, silicon etc. The external radius of the shell is about 3500 km. The Earth's mantle adjoins with a thickness of about 2900 km. Its constituents are compounds of mainly lighter elements like silicon, magnesium oxygen etc. In contrast to the electrically well conducting metallic core the mantle is practically an electric insulator.

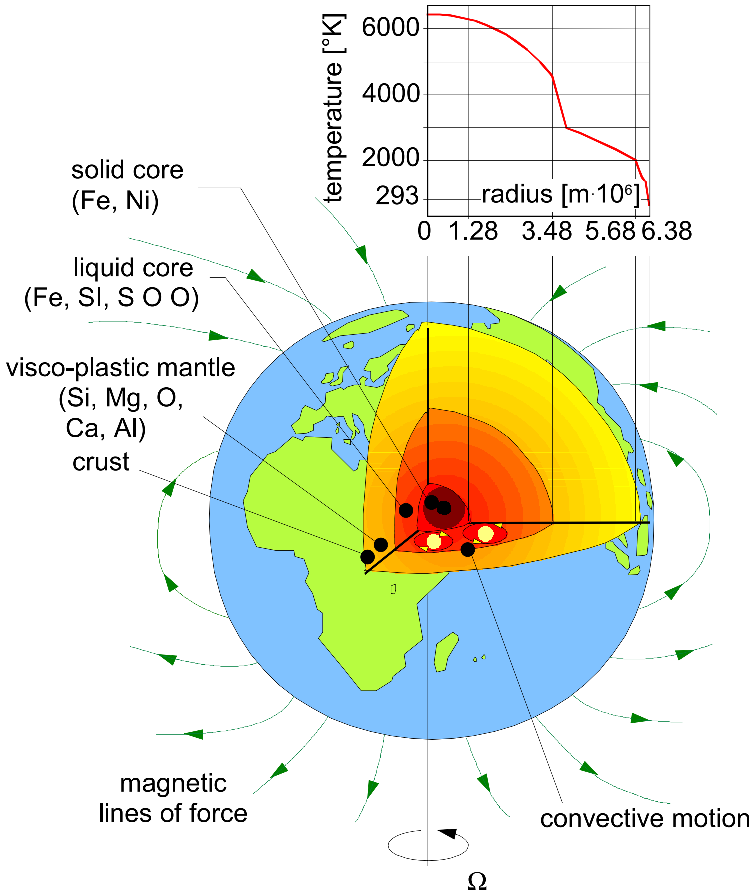

Figure 1.2. a) Structure of the Earth: solid core 1.7%, liquid core 30.8%, visco-plastic mantle 49.2%, solid tectonic plate 15.3% of the total mass after Beatty & Chaikin (1990), b) temperature distribution in the interior.

Furthermore, the heat flux balance of the surface shows that the Earth cools down permanently by loosing heat to the outer space by radiation at an average rate of about 0.04 W/m^2 and at a secular cooling rate of $5 \cdot 10^{-9}$ K/year. The Earth's static structure is shown schematically in Figure 1.2. (For more details see e. g. Fowler (1990) and Janeloz & Wenk (1988)).

Aside from the static structure of the Earth, fluid motions in the liquid core are of particular importance for dynamo action. Using thermodynamic reasoning it is commonly argued that density differences in the liquid core drive buoyant convection. The density differences may originate from temperature- or from concentration gradients of lighter dissolved elements. The concentration gradients are sustained by a permanent freezing of the heavier constituents, iron and nickel, of the liquid core at the solid inner core boundary. By rejection from the freezing material lighter components get accumulated in thin liquid layers adjacent to the inner core boundary. These concentration boundary layers are strongly buoyant and induce large-scale convective flows by repeated release of concentration plumes into the bulk liquid core. The freezing process in turn is caused by the permanent heat losses of the Earth and is simultaneously a permanent thermal energy source by the release of latent heat. Overall, the buoyant driving force for convection has been assessed to originate from concentration inhomogeneities by 80 % and from temperature gradients by 20 % (cf. Fearn (1998)). The convection velocity in the liquid core is commonly inferred from the observed westward drift of the Earth's magnetic field, and its characteristic scale is estimated as $|v| \approx 3\text{-}6 \cdot 10^{-4}$m/s (cf. Busse (2000), Roberts & Glatzmaier (2000)). Gravity forces and spherical symmetry, however, do not govern the direction of transport, rather the rapid rotation of the Earth does. Therefore the Coriolis forces strongly influence the transport process, and the motion gets essentially restricted to planes perpendicular to the axis of rotation. (For more information about the thermo-fluid dynamic behaviour of the core see e.g. Braginsky (1964) and Braginsky & Roberts (1994)).

Analytical considerations of Busse (1975) and recent numerical model calculations by several other authors (see e.g. Zhang (1992), Kageyama & Sato (1997), Tilgner & Busse (1997)) have shown, that this effect may lead to the formation of a ring of parallel convection rolls whose axes are aligned with the rotation axis of the spherical body and which touch the solid inner core at the equator. Each convection roll is sidewise confined by the highly viscoplastic material of the mantle. The deceleration of the convection at the two ends of the rolls induces an inward directed spiral flow near the roll axis, which may even be reenforced by a buoyant downdraft. For symmetry reasons the convection occurs mirror symmetrically in the northern and southern hemisphere. A sketch of Busse's columnar vortex model is shown in Figure 1.3.

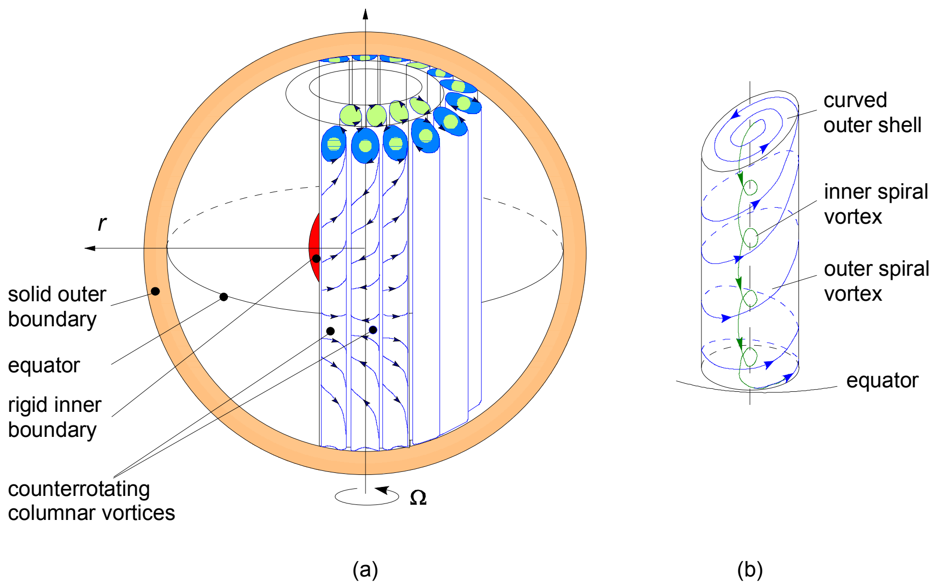

Figure 1.3. a) Columnar vortex pattern of buoyancy driven convection in a rapidly rotating spherical shell after Busse (1970) b) sketch of streamlines within a vortex.

Thus, there are substantiated arguments that a comparatively well-ordered arrangement of columnar vortices with helical velocity distribution exists in the highly conducting liquid core of the Earth. This conception has received a convincing confirmation by some model experiments of Carrigan & Busse (1983). In his experiments Carrigan rotates a liquid filled spherical shell at high rotation rates (typically 1000 rpm). Simultaneously the outer shell surface is heated and the inner one is cooled (see Figure 1.4a for the conceptional design of the experiment). In the strong centrifugal field, which may simulate the gravity field of the Earth in the model-experiment, convection rolls develop parallel to the axis of rotation. Carrigan visualised the flow pattern by flow tracers. This is seen in Figure 1.4b. There are, however, also objections against the relevance of this flow pattern in the Earth's interior, which result from model calculations under various assumptions (cf. Fearn (1998)). A strong argument in this connection is the instability of the columnar vortex pattern, when Lorentz forces of the Earth's magnetic field act on it.

Aside from the chemico-thermal energy source, the flow in the Earth's liquid core may be sustained by rotational energy as an inertia driven precession flow, originating from the weakly oblate shape of the Earth, her orbiting the sun with an inclination angle of 23° of the rotation axis to the ecliptic and the torsional momentum exerted on the rotation axis by the sun's and moon's gravity forces. Precession flow is characterized by large scale motion with some free shear layers which may become unstable and develop similar cellular structures like buoyant flows in rapidly rotating liquids (see Malkus (1963, 1968, 1994), Busse (1971), Lorenzani & Tilgner (2001)).

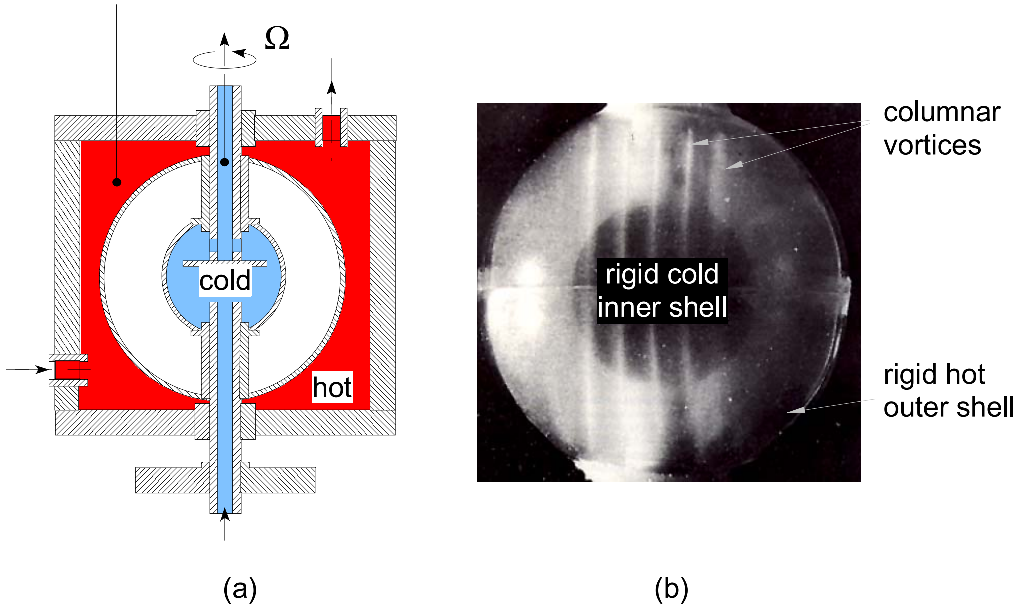

Figure 1.4: Test apparatus of Carrigan & Busse (1983), a) design of the test section, b) visualisation of Taylor-Proudman columns by light reflecting flow tracers mixed into the test fluid.

In the past it has also been speculated (see Bullard (1949), Fowler (1990), that the main driving energy could be released as thermal energy by the decay of dissolved radioactive constituents like Uranium U^{238}, U^{235}, Thorium Th^{232} and Potassium K^{40} in the Earth's core. This idea has been discarded as not well supported by observable facts.

2. Dynamo Models

2.1 Heuristic Dynamo Models

The essential feature of homogeneous dynamos is an electrodynamic feedback amplification of an initially existing seed magnetic field by stretching and distorting lines of force in sheared vortex flows of electrically well conducting fluids. Three fundamental laws of electrodynamics govern this process. Figure 2.1 displays two of them exemplarily for a straight wire conductor.

Current carrying conductors are surrounded by closed lines of force (Figure 2.1a, Ampere's law), and electric currents are induced in conductors moving perpendicular to lines of force (Figure 2.1b, Faraday's law). The other crucial property of highly conducting fluids is the quasi-freezing of magnetic field lines into the fluid. Thus, they may get stretched, twisted and folded like elastic strings. By stretching of lines of force mechanical work is done and converted into magnetic energy. A combination of such processes together with a reconnection of lines of force due to the weak diffusion of the magnetic field on short length scales may form the ingredients for a homogeneous fluid dynamic dynamo. Alfvén (1950, 1963) and Vainstein & Zeldovich (1972) combined these effects and proposed conceptional dynamo models. Figure 2.2 shows schematically the combined effects. A shear flow leads to a bulging of field lines, a subsequent torsional flow to a loop formation, a field diffusion near the crossing spot results in a reconnection of lines of force and convection to their separation. Finally, a stretched original and a separated new closed line of force coexist. The latter gives rise to an electric current in the direction of the original one. The mechanically induced current density *j* may be assumed in a first approximation as proportional to the original magnetic field *B*. This effect is crucial for dynamo action and is known in the literature as α-Effect.[1)]

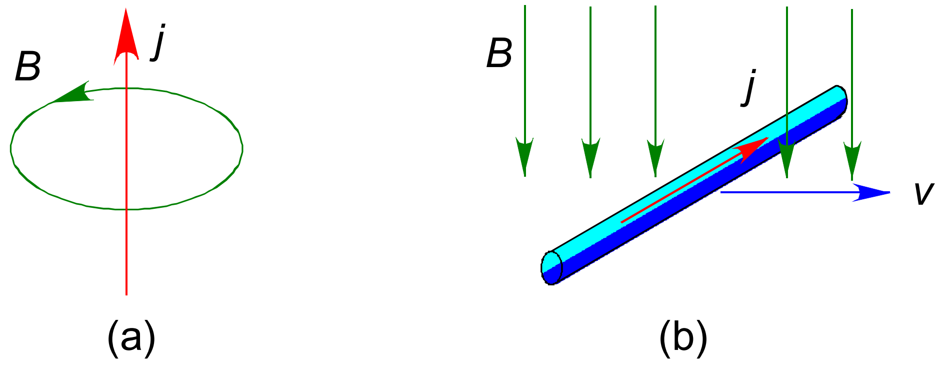

Figure 2.1. Fundamental laws of magnetodynamics, a) Ampère's law, b) Faraday's law. Here *B* indicates the magnetic field*, j* the current, *v* the velocity.

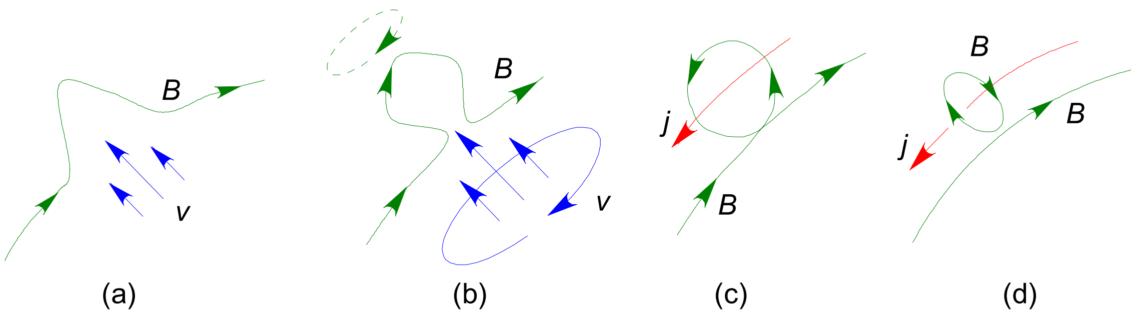

Figure 2.2: Transport of magnetic flux lines *B* in electrically conducting fluids: a) stretching by a velocity field *v*, b), c) twisting by a vortical velocity *v*, d) reconnection of the *B*-field by diffusion.

If this process is repeated at the newly formed closed line of force, a secondary distortion may lead to a reenforcement of the original one and thus to a self-amplification. This is a complete hydrodynamic dynamo cycle. Because of the twice-repeated stretching, torsion and reconnection processes

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[1)] The terminology dates back to Steenbeck et al. (1966)).

it is called the α^2-dynamo. Figure 2.3a shows how the idea of an α^2-dynamo process may be applied to the Earth's geometry. If one assumes that in the highly conducting liquid core of the Earth a turbulent vortex flow of preferred orientation exists because of the Earth's rotation, then an external initial seed magnetic field B_0 will generate a short-circuited current j_o within the spherical conductor which is parallel to the lines of the seed field. This current develops a closed toroidal magnetic field B, accompanied by a toroidal current j, as a consequence of a secondary α-Effect. A magnetic field B_2 is associated to this current and is aligned to the original seed field and thus reenforces it. A chain mechanism leads to self-amplification. This would result in an unlimited growth of the magnetic field, unless Lorentz forces reshape the flow field, and a non-linear feedback process enforces a growth limitation.

There is yet another geophysically relevant dynamo mechanism based on a differential rotation within the Earth's liquid core which may be inferred from the observed westward drift of the Earth's magnetic field. Seed lines of force penetrating the Earth are stretched and rolled up toroidally by the global rotational shear flow as depicted in Figure 2.3b(1+2). This process is called the Ω-Effect.

If subsequently an α-process, caused by upwelling small scale swirling flows, acts on the stretched torroidal field lines, a self-amplification cycle can take place. This is sketched in Figure 2.3b (3+4). This is called the α-Ω-dynamo process. It was first proposed and discussed by Parker (1955, 1979) and Levi (1976) and is often quoted as Parker-Levi dynamo.

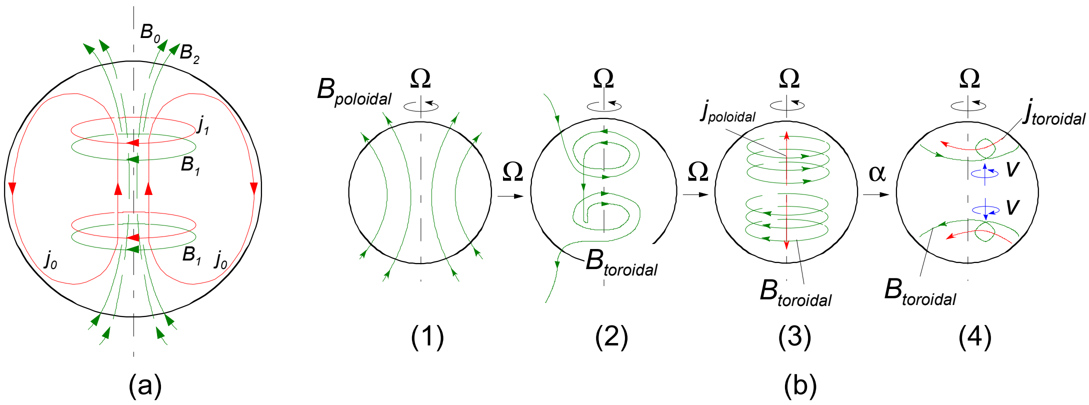

Figure 2.3. Self-excitation of seed magnetic fields by an a) α^2-dynamo, b) α-Ω-dynamo.

Today it is generally accepted that both dynamo mechanisms act synergetically in the liquid core of the Earth. More details of such heuristic models are given in earlier survey articles of Gubbins (1974), Rittinghouse-Inglis (1981), Roberts (1994) and Moss (1997). The presented heuristic dynamo models, however, are too general to describe all the observed properties of the Earth's magnetic field. If this goal is to be achieved, the fluid dynamic processes, the thermo-mechanical driving mechanism as well as the feedback of the magnetic field on the flow have to be taken into account. However, treating the complete problem mathematically is a formidable task. Therefore, for some time simpler, purely fluid dynamic dynamo models were considered. Only recently the extensive use of computational fluid dynamics (CFD) has achieved a break through in the development of realistic geodynamo models. The main results and the limitations of this development are outlined briefly in the next two sections.

2.2 Kinematic Dynamo Models

Although the full thermo-fluid dynamic dynamo problem, coupling the flow and the magnetic field generation process, was discussed already by Bullard & Gellman (1954) and mathematically formulated by Braginskii (1964), methodical difficulties and lack of computational power enforced a reduction of the complete problem to simpler, so-called kinematic dynamo models. Such models start from given plausible mass conserving laminar velocity fields compatible with the particular geometries e.g. spherical ones.

A mathematical method to solve the kinematic dynamo problem for laminar incompressible flow in spheres was first presented by Bullard & Gellman (1954). Using their methods Pekeris et al. (1973) showed that the Bullard & Gellman solution was faulty (the series expansion of their solution does not converge), and they derived valid dynamo solutions for a class of three-dimensional, helical perfect flows in spherical geometries. With the aid of an early generation of electronic computers Kumar & Roberts (1975) and Dudley & James (1989) investigated some particularly simple flow modes of this class which give dynamo action for as low as possible magnetic Reynolds numbers Rm. The magnetic Reynolds number Rm is the crucial parameter for the onset of dynamo action in the kinematic problem. It is defined as $Rm = UL/\lambda$, where U is a reference velocity of the system, L a length scale measuring the geometrical dimension and λ the magnetic diffusivity measuring the decay of the magnetic field by Ohmic losses. Some of these low order flow patterns are sketched in Figure 2.4a-c. Dudley & James find that these helical flows require magnetic Reynolds numbers $Rm \geq 50$ for dynamo action. The dynamo magnetic fields have dipolar or quadrupolar character.

Apart from the outlined systematic approach for velocity fields of spherical symmetries, Herzenberg (1958) first proved mathematically self-excitation of magnetic fields. He started from a simple kinematic system consisting of two small rotating rigid conducting spheres embedded in a large non-rotating conducting sphere. Although he refers in his work to "Geomagnetic Dynamos" he also states: "It certainly is not suggested that the motions in the Earth's core are so simple".

Ponomarenko (1973) and Gailitis & Freidberg (1976) derived rigorous mathematical solutions of the dynamo problem for simple axisymmetric velocity distributions. The helical velocity distribution is given by a rotating cylindrical conductor moving in axial direction and being embedded in a conducting infinite medium at rest (see Figure 2.4d). Gailitis et al. (1989) considered other cases for which the embedding medium has a finite extent. They predict onset of magnetic self-excitation for magnetic Reynolds numbers Rm >12 based on the radius of the rotating cylinder.

Steenbeck et al. (1966) achieved a break through in dynamo theory, when they introduced Reynolds' concept and mathematical methods for turbulent flow into magnetohydrodynamics by splitting the fluid dynamic and the electromagnetic quantities in a mean- and a fluctuating part. This so-called *Mean Field Theory* was elaborated by Krause & Rädler (1971,1980) and applied to turbulent velocity fields in spherical geometries of very general character. Their consistent and rigorous theory was capable to describe the α-Effect (see previous section) quantitatively and predict dynamo action in spherical geometries.

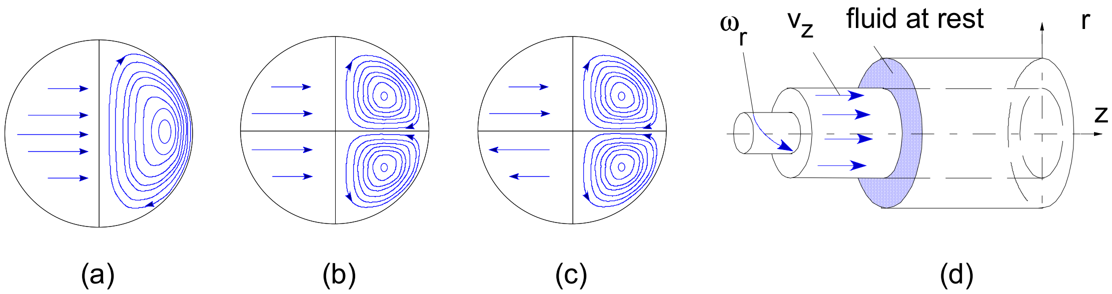

Figure 2.4. Principle flow pattern of helical vortices a)-c) in the spherical geometry with projections of the toroidal (left) and poloidal (right) velocity components according to Dudley & James (1989). d) Principle sketch of the flow pattern in the Ponomarenko dynamo.

Another relevant velocity pattern suitable as a test case for dynamo action is the regular arrangement of columnar vortices which is conjectured to occur as a characteristic flow pattern in the Earth's liquid core (see section 1.2). G. O. Roberts (1970, 1972) investigated first systematically periodic helical vortex flows. Busse (1978, 1992) following an idea of Childress (1970) adapted the Roberts' periodic vortex pattern to planetary conditions by encapsuling a section of this pattern into a finite cylindrical domain. Later, for computational reasons, Tilgner (1997a,b) and Raedler et al. (1998) have chosen a spherical confinement. The flow patterns are depicted schematically in Figure 2.5. It is remarkable that Gailitis (1967) proposed a similar concept for a laboratory dynamo, which, except for his model calculations, was not furthermore pursued in the literature.

Busse (1992) solved the kinematic dynamo problem for the limited size vortex pattern using a mathematical two-scale approximation. He found that a self-excited quasi-dipolar magnetic field occurs for surprisingly low magnetic Reynolds numbers Rm < 10. He recognized the chance of using such an arrangement to demonstrate experimentally the existence of homogeneous dynamos, since low values of the marginal Reynolds number generally reduce the required technical efforts for such experiments. Indeed, he proposed such an experiment in 1979 (Busse (1979, 1992)).

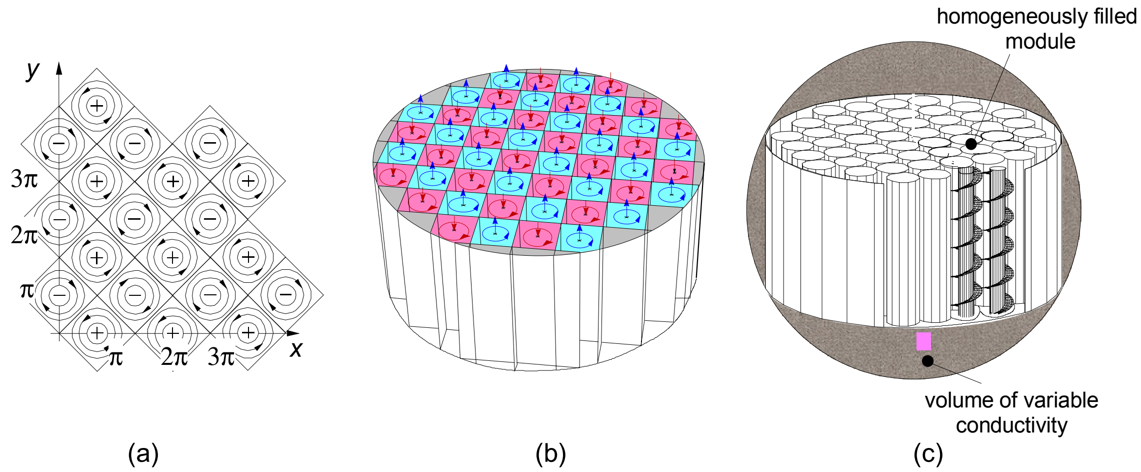

Figure 2.5. Unconfined and confined periodic vortex fields as a basis for dynamo action. a) Roberts' periodic vortex field, b) Busse's vortex arrangement in a cylindrical domain, c) Tilgner's (1997) and Rädler's (1998) spherical containment.

2.3 Convection Driven Geodynamo Models

The fast development of super computers during the last decades has greatly advanced the treatment of magneto-fluid dynamic geodynamo models coupling the thermo-fluid dynamic and the electrodynamic processes in the Earth's interior. For this, in essence, a set of coupled partial differential equations for the transport of mass, momentum, heat and magnetic induction has to be solved numerically for the flow and the magnetic field in a fast rotating spherical shell filled with a well conducting liquid. Several research groups in different countries have now tackled this problem. Busse (2000), Zhang & Schubert (2000) and Roberts & Glatzmaier (2001) have compiled a survey on such activities in review articles. Some, at first glance spectacular results have been obtained.

The works of Glatzmaier & Roberts (1995, 1997) and Glatzmaier et al. (1999) are a landmark in this development. These authors calculate a magnetic dipole field for a spherical geometry with dimensions similar to the Earth assuming a given heat flux at the inner core boundary (Figure 2.6). Performing long-term computations they even find events of magnetic field reversals, which, in their case, occurred in periods between 40 and $150 \cdot 10^3$ years. Moreover, they predict a differential rotation between the solid inner core and the outer solid shell, the mantle, which could possibly explain the weak westward drift of the non-dipolar constituents of the Earth's magnetic field. While the first two phenomena are characteristic for the Earth's magnetic field, the calculated differential rotation, although suggestive, has not yet been confirmed unambiguously by independent geophysical measurements (compare Song & Richards (1996), Su et al. (1996), Souriau et al. (1997) and Souriau (1998)).

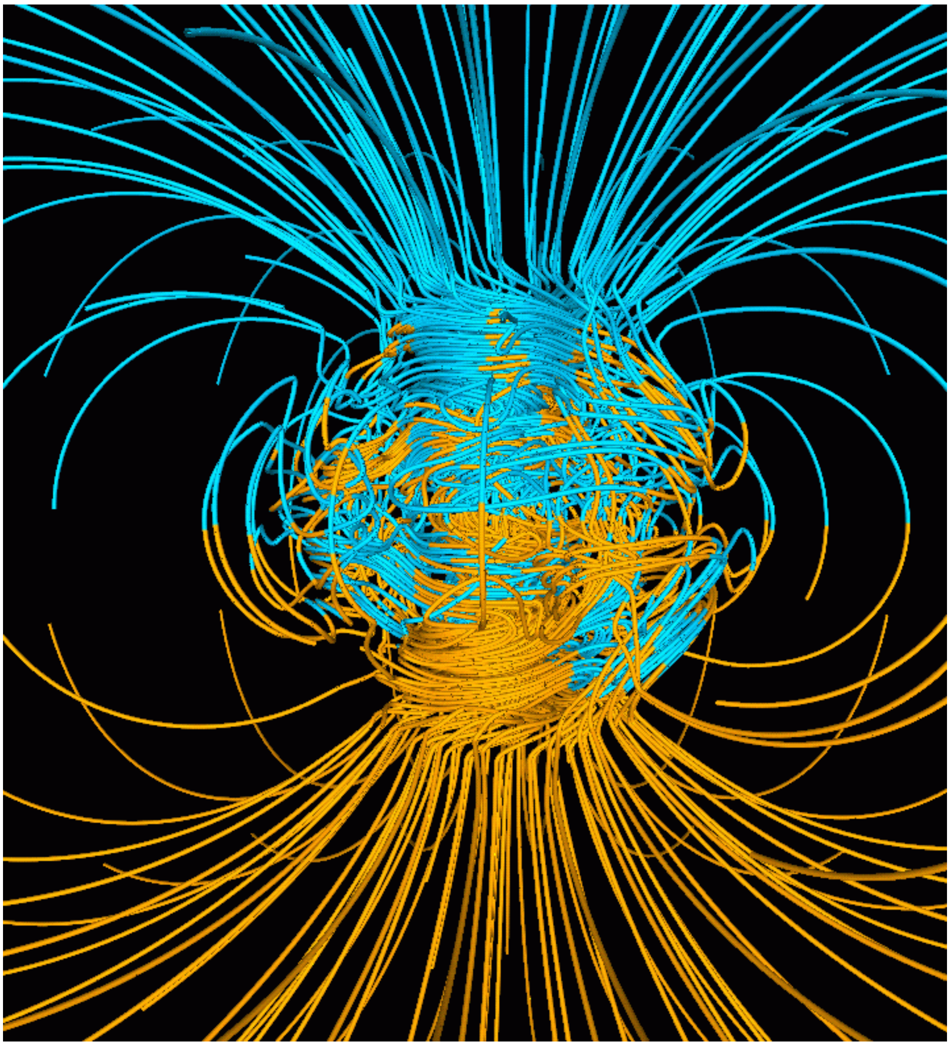

Figure 2.6. A three-dimensional magnetic field structure simulated by the Glatzmaier-Roberts geodynamo model. The field lines are drawn out to two Earth's radii. The magnetic field is wrapped around the " tangent cylinder " to the solid core due to the shear of the zonal fluid flow (after Glatzmaier & Roberts (1995)).

Sarson & Jones (1999) have corroborated the findings of Glatzmaier & Roberts (1995) and Ochi et al. (1999) using an equivalent numerical approach. On the other side other researchers using numerically different approximations found a quite different dynamical i.e. temporal behaviour of the magnetic field (e.g. Christensen et al. (1999), Morrison & Fearn (2000), Grote, Busse, & Tilgner (2000)). In particular polarity changes of the magnetic field were not observed although a variety of regular and chaotic dipolar magnetic fields were calculated and could even be classified according to specific parameters characterizing the internal flow. (For more details see Busse (2000) and Roberts & Glatzmaier (2001)). A typical result of the direct numerical simulation by Grote et al. (2000) is shown in Figure 2.7, which demonstrates the coherent columnar flow structures as well as the character of the magnetic field in terms of field line projections.

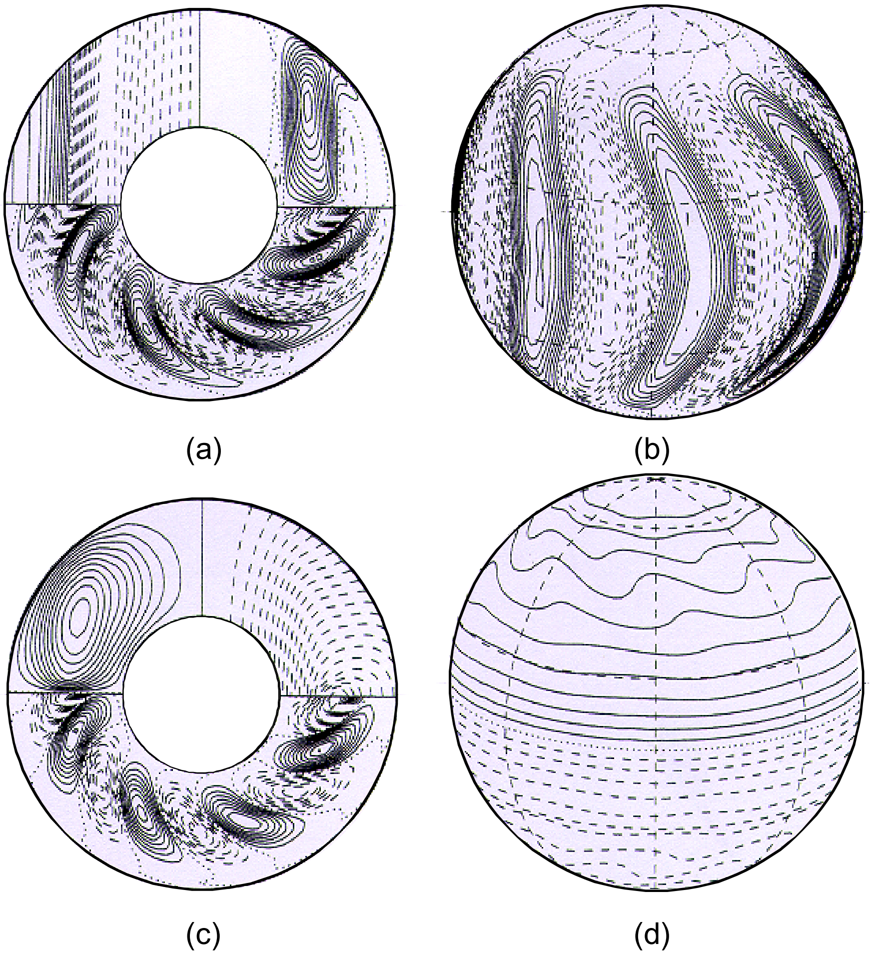

Figure 2.7. Example of a stationary dipolar dynamo calculated by Grote, Busse & Tilgner (2000). The upper left graph shows lines of constant zonal flow (upper left quarter), meridional streamlines of the axisymmetric component (upper right quarter) and streamlines in the equatorial plane (lower half). The upper right graph denotes lines of constant radial velocity at the middle surface of the fluid shell. The lower left plot shows lines of constant zonal component of the magnetic field (upper left quarter), meridional field lines of the axisymmetric component of B (upper right quarter), and field lines of the non-axisymmetric component of B (lower half). The lower right plot shows lines of constant radial component of the magnetic field at the sphere's surface.

In spite of the spectacular results obtained by such numerical simulations, there still exist some fundamental difficulties in the numerical approach of a geodynamo theory. Magneto-fluid dynamics in the Earth's interior is governed by a large number of physical parameters such as the rotation rate Ω, the heat flux from the solid core q_c or a heat source density Q_c, the mass density ρ and the driving density gradient $(\Delta\rho/\Delta r)$ in the liquid core, the material properties in terms of the diffusivities for heat κ, for momentum ν, for electricity η and the core geometry i.e. the thickness of the liquid core d. These properties may be combined into dimensionless groups describing the essential physical phenomena in terms of power ratios of buoyancy and Coriolis forces on the one side and dissipation by the different diffusivities on the other side. This results in four independent groups, the Ekman number, the Rayleigh number, the thermo-fluiddynamic Prandtl number and the magnetic Prandtl number respectively defined as

$$Ek = \frac{\nu}{2\,\Omega\, d^{2}}, \quad Ra = \frac{(\Delta\rho\,/\,\rho\,)\,g_{o}\ d^{3}}{\kappa\nu}, \quad Pr = \frac{\nu}{\kappa}, \quad Pm = \frac{\nu}{\eta} \ .$$

For the Earth's liquid core these numbers have typical values of the order $Ek \sim O(10^{-15})$, $Ra \sim O(10^{17})$, $Pr \sim O(10^{-1})$, $Pm \sim O(10^{-6})$ (cf. Busse (2000), Roberts & Glatzmaier (2001)).

Closed flow convection at these extreme values of the control parameters exhibits very thin free shear and boundary layers. A simultaneous numerical resolution (in space and time) of the bulk flow and the thin, singularly behaving shear layers is not feasible with the presently existing computer capacity. To render the dynamo problem numerically treatable, computational artefacts have been introduced which all are aimed at reducing the span of length and time scales occurring in reality. Means that were used so far to overcome this difficulty are the introduction of enhanced diffusivities[2)], in this context called "hyperdiffusivities", and, alternatively, a strong reduction of the numerical resolution in one spherical coordinate, mostly in the azimuthal direction. All these measures result finally in a significant modification of the governing dimensionless quantities *Ek, Ra, Pr, Pm* compared to the best estimate values of the Earth's core, in order to render these computations feasible. So far available results from numerical computations are limited to values $Ek \geq 10^{-6}$, $Ra \leq 10^{6}$, $Pr \geq 0.1$, $Pm \geq 0.1$ (cf. Busse (2000)).

It is obvious that there still exists a significant gap between computationally accessible geodynamo states and the factual geodynamo. Another puzzling observation from parametric studies by Zhang and Jones (1997) and Grote et al. (2000) is the sensitivity of the flow and magnetic field structure on the numerical "adjustment" parameters or on a variation of the property parameters *Pr* and *Pm*. Thus, even in spite of the already available computer power there is uncertainty about the validity of the currently debated computational geodynamo models. These facts have stimulated discussions and efforts to provide measured data from generic dynamo experiments, which may be used to either improve the physical understanding of the phenomena or to validate the numerical dynamo models.

3. Supporting Experiments

3.1 Fundamental Experiments

A crucial ingredient of dynamo action is the freezing in phenomenon of magnetic field lines in highly conducting liquids i.e. liquid metals such as mercury, gallium and sodium. Due to this phenomenon the stretching and twisting of field lines occurs which generate the α- and Ω-Effects in dynamos (see section 2.1). Lehnert (1957) demonstrated in a fundamental experiment that by stirring liquid sodium in a cylindrical container an initially stationary poloidal magnetic field is deformed by the azimuthal velocity to generate significant toroidal components inside the sodium. A principle sketch of Lehnert's experiment is shown in Figure 3.1a. Recently a French group (cf. Odier et al. (1998), Marie et al. (2001)) performed a systematic experimental study of this phenomenon including the effects of turbulence. This group measures the deformations of an external magnetic field imposed on a van Kàrmàn swirling flow between two rotating discs in a cylindrical container. The test facility is sketched in Figure 3.6b. They find that the advectively induced magnetic field components may achieve the intensity of the externally applied field.

Steenbeck et al. (1967) proposed and conducted another fundamental experiment to prove the α-Effect, namely the induction of an electric potential difference and as a consequence a current flow along the mean magnetic field lines. Gailitis and Kirko (see Steenbeck et al. (1967)) forced a liquid sodium flow through two meandering flat channel systems with copper walls, which were intertwined to one another (see Figure 3.1b). An external magnetic field penetrating the channel package perpendicular to the parallel channel sections is then repeatedly twisted when crossing over from one to the next channel. Thus the effect of a non-symmetric swirling flow is simulated. In the experiment a potential difference could be measured along the direction of the imposed magnetic field which was on the whole proportional to its intensity and to the square of the fluid velocity as predicted by the *Mean Field Theory* of Steenbeck et al. (1966).

Deliberations on constructing a homogeneous hydrodynamic dynamo in the laboratory have to start from the requirement that the mechanical power input be at least equal to the Joule dissipation occurring under self-excitation of a magnetic field i.e. the magnetic Reynolds number should be larger than, say, 1 (see section 2.2). Joule dissipation is proportional to the magnetic diffusivity η, which in turn is inversely proportional to the electrical conductivity σ and the magnetic permeability μ as

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[2] These enhanced diffusivities resemble in some way Prandtl's mixing length model for turbulent flow when applied to a multi-scale turbulent vortex flow.

$\eta = 1/(\sigma\mu)$. For a drastic reduction of Joule dissipation one may either increase σ or μ. In order to increase σ well conducting liquid metals such as mercury or liquid sodium may be used as a test fluid with a permeability μ close to that of the vacuum. μ can only be significantly increased by using ferromagnetic materials such as iron or specific iron alloys, which have a moderate electrical conductivity, but a magnetic permeability enlarged by a factor of 1000 and more compared to other metals.

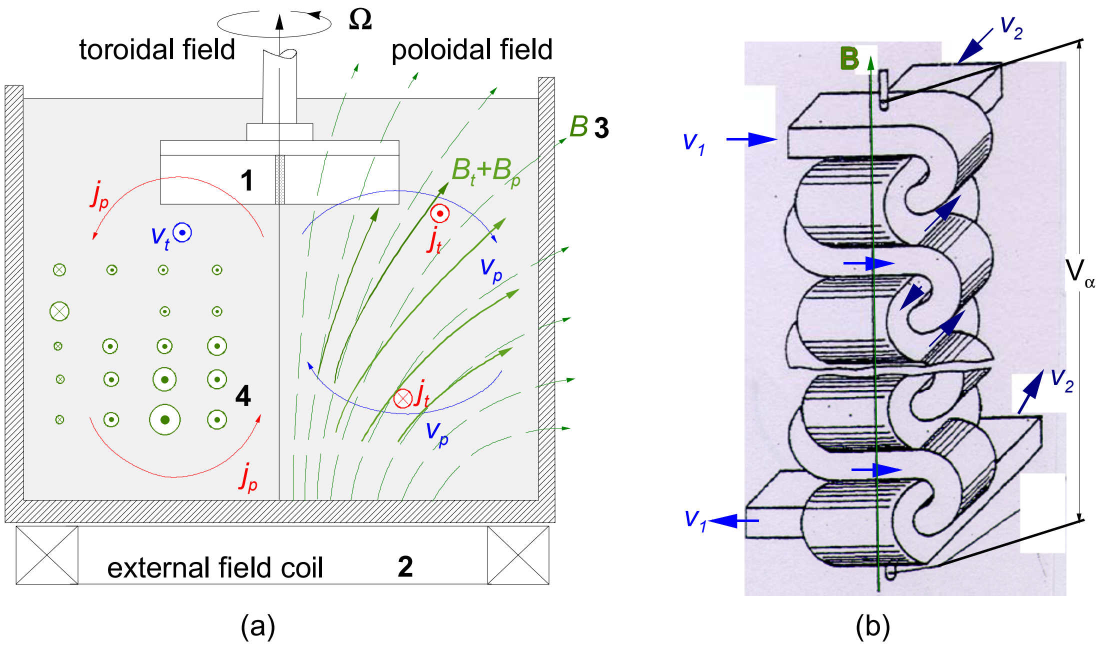


Figure 3.1. a) Lehnert's (1957) experiment of stirred sodium in a cylindrical container penetrated by an external magnetic field: 1 stirring propeller, 2 coil for external field generation, 3 initial poloidal magnetic field, 4 induced toroidal magnetic field components. b) Principle sketch of the Riga α-Effect experiment by Steenbeck et al. (1967).

Using ferromagnetic material and rigid body rotation Lowes & Wilkinson (1963, 1968) constructed the first operating homogeneous laboratory dynamos based on the model concept of Herzenberg (1958). They fitted two rotating iron cylinders with axes of rotation at an angle of 90° to each other into cylindrical cavities sunk into a solid block of iron alloy, and they used mercury as a hydraulic lubricant and electrical transmitter of currents. A principle sketch of one of their test apparatuses is seen in Figure 3.2a. They reported spontaneous magnetic self-excitation in their facility for rotation rates beyond certain high angular velocities (400 r.p.m.). In different experimental arrangements they observed several phenomena such as oscillations and polarity transitions of the magnetic field, which they claimed to show many features in common with the observed geomagnetic field. However, the strongly non-linear dependence of the magnetic permeability μ of ferritic materials on the magnetic field itself caused material dependent hysteretic behaviour in form of jump excitation or decay (see Figure 3.2b) which is hard to predict by a simple dynamo theory and which has not been observed in geomagnetism.

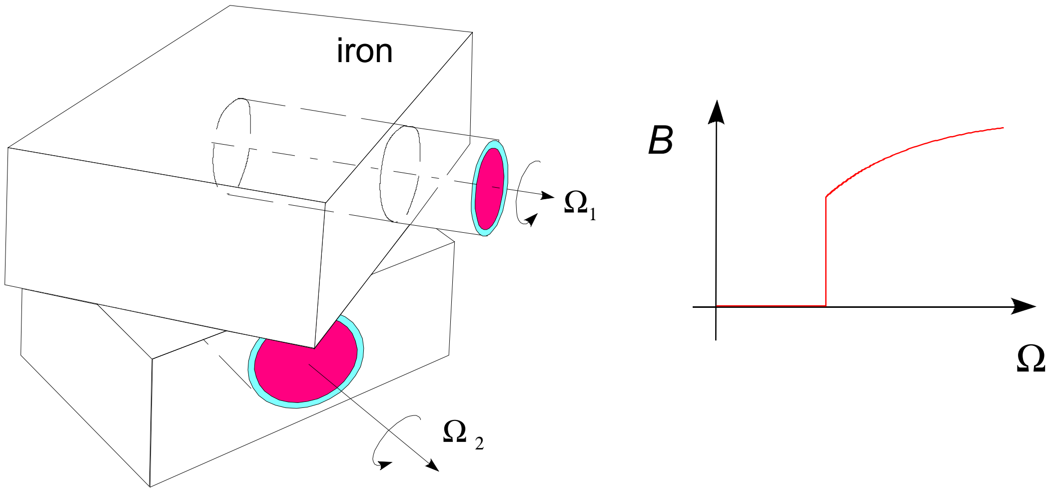


Figure 3.2. a) Principle sketch of the Lowes & Wilkinson (1968) laboratory model of the Geomagnetic Dynamo, b) saturation of magnetic induction as a function of the angular velocity Ω.

3.2 Fluid Dynamic Experimental Dynamos

3.21 Performed Dynamo Experiments

The first two successful experiments on hydrodynamic kinematic dynamos were performed by Gailitis et al. (2000) and Müller & Stieglitz (2000, 2001) in collaboration with other research groups (Stefani et al. (1998, 1999), Busse (1992), Tilgner (1997a,b.), Rädler et al. (1996, 1998, 2002)). The design of the two test facilities in Riga and Karlsruhe respectively are based on two different dynamo models, Ponomarenko's (1973) confined axial swirling flow on the one side and the Roberts-Busse confined columnar helical vortex pattern on the other side (see section 2.2). The self-excitation mechanism for the two dynamo models is quite different. Stretching and bending of the lines of force in curved boundary shear layers together with their reconnection by diffusion leads to self-amplification in the Ponomarenko flow (see Tilgner (2000)). In case of the Roberts-Busse velocity distribution a repeated stretch-twist-diffusion process known as α^2-process induces dynamo action. The experimental simulation of the Ponomarenko flow is achieved in the Riga test section by an arrangement of three cylindrical coaxial stainless steel pipes of 3 m length. The test fluid is sodium. In the central pipe a swirling flow is maintained by a properly designed freely spinning impeller at the entrance. At the outlet the flow is returned vortex free into the adjacent first annular gap by means of guide vanes. The second annular pipe space contains only stagnant liquid sodium to provide a conducting environment. The test section and some technical data are sketched in Figure 3.3a. Calculations by Stefani & Gerbeth (1998, 2000) based on analytical and numerical models predict self-excitation of a magnetic field for magnetic Reynolds numbers Rm ≥19 and traveling electromagnetic waves along the pipe axes, i.e. an oscillating time signal for the induced magnetic field should be observed. Furthermore, sensitivity calculations have shown that the onset of self-excitation depends significantly on the velocity distribution within the swirling flow. Thus, much effort has been placed on the proper hydrodynamic design of the pump impeller and the guide vane system and its validation by velocity measurements (Stefani & Gerbeth 1998). The self-excitation process can be seen from the measured time signal of the magnetic field and the recorded rotation rate of the impeller shown in Figure 3.3b taken from Gailitis et al (2001). The graph shows that self-excitation starts beyond a threshold value Ω~1950 rpm of the impeller rotation rate and leads to a saturated oscillatory magnetic field, if the rotation rate is kept constant. The latter phenomenon indicates the feedback of the generated magnetic field on the flow by the electrodynamic Lorentz forces. This is considered to be also a crucial mechanism of the dynamo process in the Earth's interior.

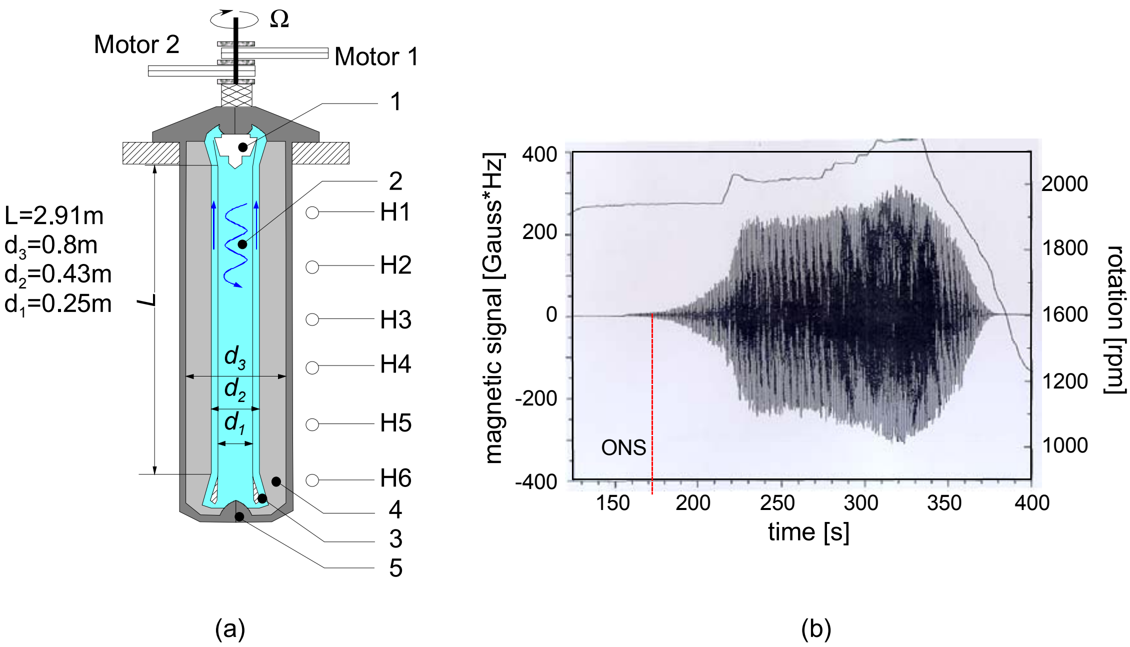


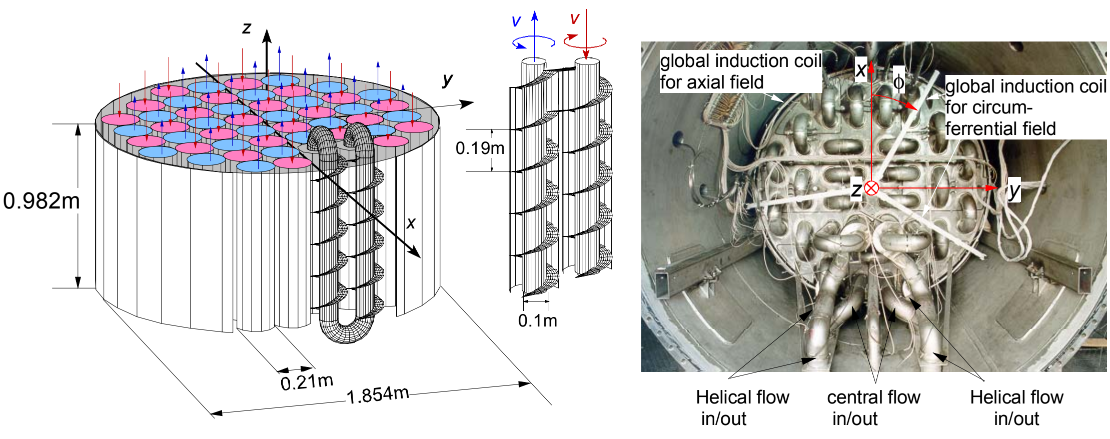
Figure 3.3. a) The Riga test section, test fluid sodium: 1 Impeller, 2 helical flow region, 3 vortex free return flow channel, 4 stagnant sodium, 5 stainless steel container, $H_1 \rightarrow H_6$ Hall probe sensor positions. b) Measured time signal of radial component of the self-excited magnetic field; (—) recorded rotation rate of pump impeller; (.....) and (ONS) onset of self-excitation (Gailitis et al. (2001)).

Locating 52 vortex generators in a cylindrical container and interconnecting them at the flat cylinder surfaces by bends and fitting pieces technically realize the Roberts-Busse flow pattern. The individual vortex generator is constructed as a cylindrical coaxial channel with a helical baffle in the annular gap. A schematic sketch of the design and its dimensions is shown in Figure 3.4a. There are in principle two independent channel systems, the central channels interconnected by 180° bends and the annular channels with helical flow interconnected by fitting pieces. Sodium is used as a test fluid, which fills the piping system as well as the free space in the cylindrical container. The sodium is circulated in the central and helical circuit by external magnetohydrodynamic pumps. A photograph of the Karlsruhe test module is seen in Figure 3.4b. (For more technical details see Stieglitz & Müller (1996)) The operation of the test facility has resulted in the following main results (Stieglitz & Müller 2001):

1. If a critical combination of flow rates in the helical and central channels is exceeded a stationary magnetic field of quasi-dipolar character is established. The axis of the dipole is perpendicular to the cylinder axis of the test module.

2. Significant magnetohydrodynamic pressure losses in addition to the frictional losses are observed for flow rates beyond the margin of self-excitation indicating the feedback of the magnetic field on the flow field due to growing Lorentz forces.

3. The observed magnetic field is not perfectly steady; it rather fluctuates about the mean value of the magnetic field by about 5-10 %.



(a) (b)

Figure 3.4. a) Principle sketch of the Karlsruhe dynamo module. b) Photo of the technical performance of the module.

The first and second observation has been predicted and explained by calculations of Tilgner (1997), Rädler et al. (1996, 1998) and Tilgner & Busse (2001) using either direct numerical, Mean Field or even analytical approaches. The third observation, the origin of the fluctuations of the magnetic field, is neither experimentally nor theoretically adequately analyzed up to now. The observations are demonstrated by the graphs of Figure 3.5.

The Riga and Karlsruhe test modules have in common that the flow is guided in relatively narrow channels and, therefore, has a limited degree of freedom. Even at high velocities turbulent fluctuations have relatively small intensity of at most 5-10% of the mean flow. The response of turbulent channel flow to a penetrating magnetic field is mainly an enhanced pressure loss through electromagnetic forces resulting in additional Joule dissipation. Major flow redistributions or even topological changes of the flow are practically excluded in high-speed channel flow. Except that the Karlsruhe test module reproduces some features of the Taylor-Proudman column assembly, as conjectured for the Earth's interior, there are distinct differences between the channel flows in the Riga- and Karlsruhe dynamo module and the free flow in the liquid outer core which is only subjected to the constraints of the Coriolis forces and the spherical boundaries.

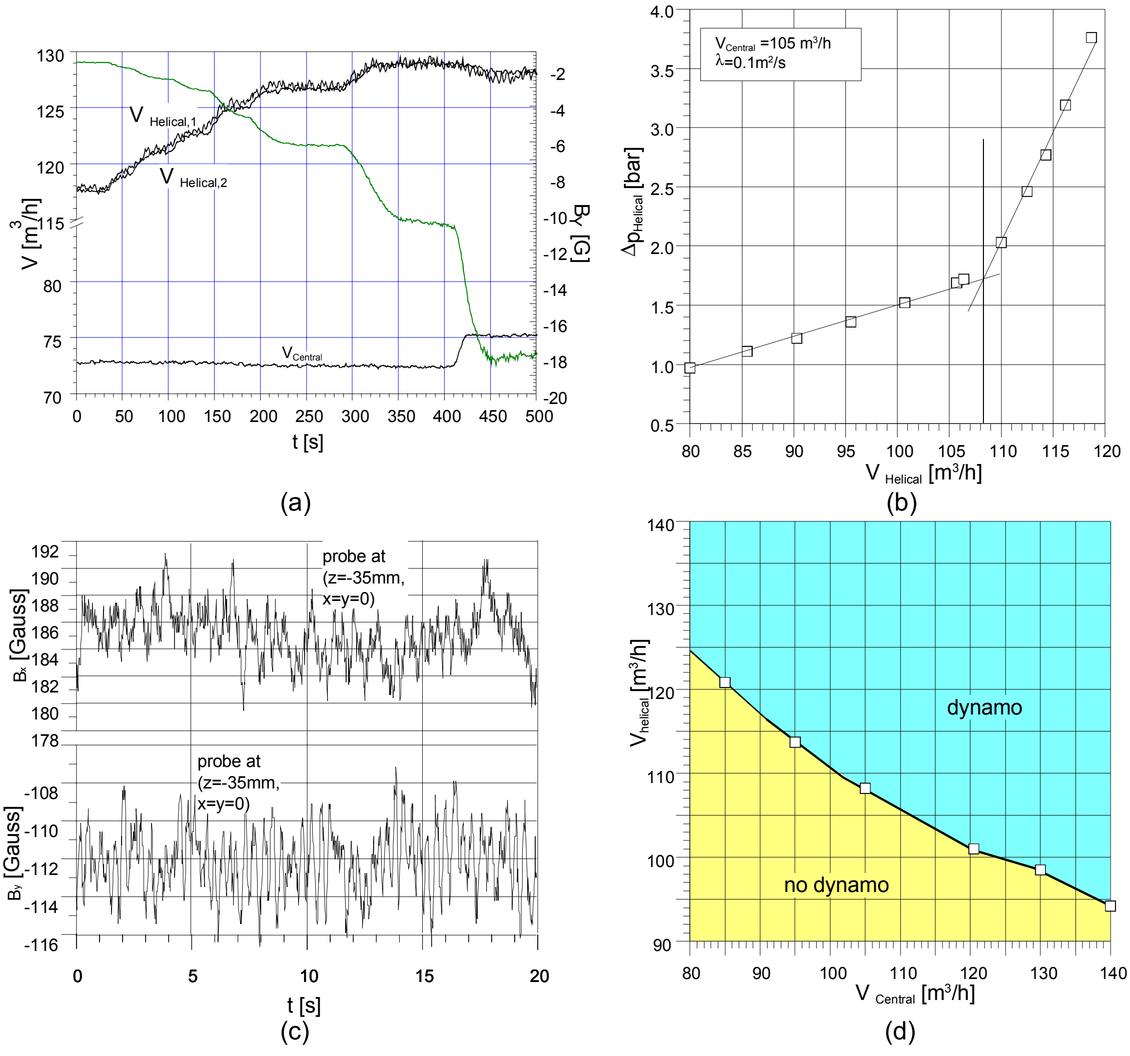


Figure 3.5. Experimental results of the Karlsruhe dynamo experiment: a) self-excitation of the magnetic induction demonstrated by the y-component By and transitions to saturation after each increase of the volumetric flow rate, b) pressure loss increase after self-excitation, c) time fluctuations of the saturated magnetic field, d) phase diagram for dynamo action.

3.22 Dynamo Experiments in Progress

The constraints of channel flow on the feedback mechanism of dynamo action can be relaxed, if a fluiddynamic dynamo can be realized in a spherical (or cylindrical) geometry, as suggested by the model solutions of Dudley and James (1989). Several research groups, Forest et al. (2000), Lathrop et al. (2000) in the US, Pinton at al. (2000) in France, have set up test facilities to achieve this goal. The particular flow patterns are to be established by placing one or two co- or counter rotating impellers on a central axis through the sphere. Figure 3.6 shows schematic sketches of such arrangements[3)]. Pinton et al. (2000) have chosen a cylindrical container. Two rotating rough discs instead of impellers (see Figure 3.6b) drive their recirculating flow. All groups use liquid sodium as a test fluid. As the onset of self-excitation depends sensitively of the velocity distribution within the sphere, great care has to be taken to develop (or choose commercially available) specific impeller designs to provide optimal flow conditions. Extensive local velocity measurements are being performed in test spheres using water as a simulator for sodium in order to assure the required quality of the flow and to start kinematic dynamo-calculations from realistic velocity distributions. The generated internal flow in the spheres is highly turbulent with fluctuations of the order of 50% and more. This feature distinguishes the spherical arrangement substantially from the channeled flows in the Riga- and Karlsruhe dynamo test facilities. These hydrodynamic dynamos are frequently termed turbulent dynamos. The near future will show if they work and what their dynamic behaviour will be.

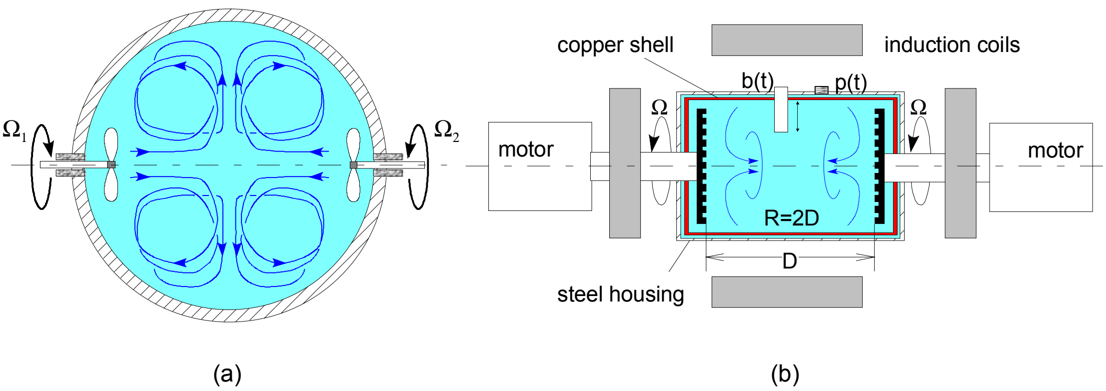


Figure 3.6. Principle sketch of the driving mechanism for the flow in spheres and cylinders to establish the Dudley & James (1989) flow topology. a) Forest et al. (2000) and Lathrop et al. (2000), b) Pinton et al. (2000).

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3) The dimensions of the different spherical test facilities vary in the diameter: D.=.0.6m and D = 3m (the latter in a rotating reference system, rotation rate ≈1 Hz; Lathrop et al.); D = 1m (Forest et al.); the required velocities are:
V = 50m/s and V = 15m/s respectively. Pinton et al. have chosen a cylindrical container with D = 0.4m and a heigth H = 0.6m.

An experiment aimed at proving the Parker (1979) α-Ω-dynamo mechanism (see Figure 2.2b) is in preparation under the leadership of Colgate, Beckley, & Romero (2001) in New Mexico, US. In a Couette flow between two coaxial cylinders, rotating at different speed, pulsed jets are generated through several nozzles perpendicular to the azimuthal main shear flow and impact on a confining rigid boundary. A sketch of the test apparatus is seen in Figure 3.7. Lines of force of a seed field are first wound up by the Couette flow (Ω-Effect) and then axially stretched and twisted in a plume type flow generated by the pulsed jets (α-Effect). According to the *Mean Field Theory*, the two sequentially repeated mechanisms would lead to dynamo action. The pulsed plumes in the Couette shear flow are expected to exhibit the same fluid dynamic effect like the buoyant plumes in the Earth's interior released from concentration layers. Fluid dynamic experiments are being performed to study details of the Couette flow and jet flow interaction. A test cell for operation with liquid sodium is under construction.

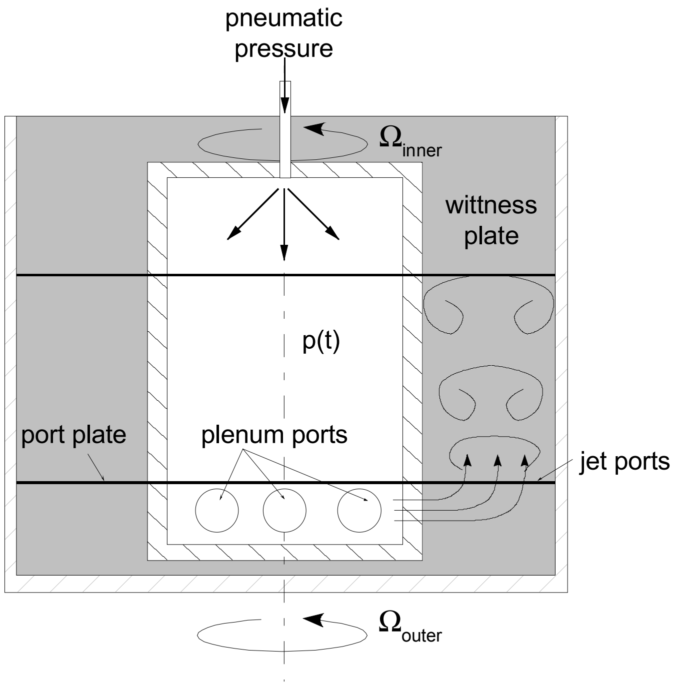

Figure 3.7. Principle sketch of the New Mexico α-Ω-dynamo experiment after Colgate et al. (2001).

Frick et al. (2001) in Russia are preparing a kinematic dynamo experiment which is based on a closed annular vortex ring which is a topological equivalent to the annular helical flow in the sphere shown in Figure 2.4b. Instead of employing an impeller drive inside the toroidal conduit, they use inertial forces in the fluid to establish a transient vortex flow of duration long and intensive enough to achieve self-excitation. This is done by setting a sodium filled toroidal conduit with built in screw type guide vanes into rigid body rotation and then brake it abruptly. Thus, the guide vanes induce an inertia driven turbulent spinning flow, which decays in time, by dissipation. At present the flow is being optimized in a test torous of median radius 0.5 m, cross-sectional radius 0.1 m and at rotation rates up to 50 Hz. The magnetic field is predicted to appear as a traveling wave in a similar way like in case of the Ponomarenko dynamo.

Following an idea of Malkus (1968) and preliminary tests of Gans (1970), a French group of scientists led by Alemany & Leorat et al. (2000) are planning a dynamo experiment which is driven by a precession flow in a container filled with liquid sodium and spinning about two axes of rotation. A conceptional sketch of their test apparatus is shown in Figure 3.8. If dynamo action in such a device could be demonstrated under conditions, which hold also for a scale up to Earth's dimensions, it would suggest a more complex synergetic process for the generation of the Earth's magnetic field. Moreover, this would also provide an explanation for magnetic fields of smaller planets and satellites such as Ganymede of Jupiter for which internal convection is unlikely to occur.

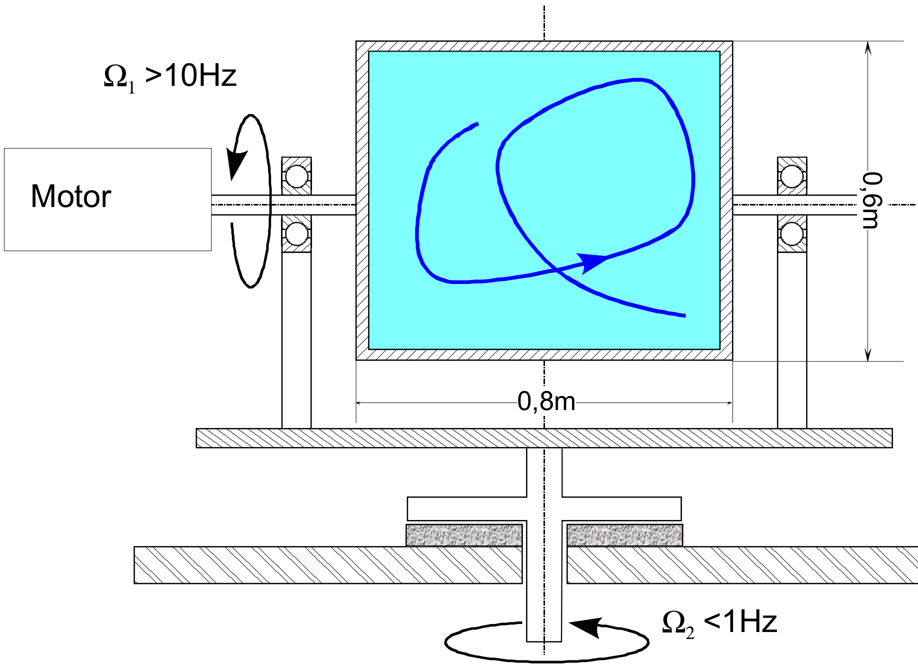

Figure 3.8. Sketch of the French precession flow driven dynamo experiment after J. Alemany et al. (2000); proposed design data: cylinder diameter: 0.6 m, height: 0.8 m, rotation rates: Ω1<10 Hz, Ω2< 1 Hz, achievable magnetic Reynolds numbers R ≤ 150.

The so far successful dynamo experiments of Gailitis et al. (2000) and Müller & Stieglitz (2000) and the ones in an advanced state of development (Forest et al. (2000), Lathrop et al. (2000), Pinton et al. (2000)) are validating kinematic dynamo models only. However, a true experimental simulation of the complete geodynamo mechanism would require generating the velocity field for dynamo action by buoyancy driven convection in a rapidly rotating test container. Lathrop et al. (2000) Are studying the feasibility of such an experiment. Starting from the experimental concept of Carrigan & Busse (1983) they are designing a spherical test module of high material strength which is filled with liquid sodium and whose outer shell can be heated while the inner is cooled. The spherical container is to be rotated at high rotation rates such that intensive convection is induced in the liquid sodium by the centrifugal field and Taylor Proudman vortex columns form under the influence of Coriolis forces in the same way as in the experiment of Carrigan & Busse (see section 1.2, Figure 1.4). Rough estimates of the design parameters give that for sphere diameters of 0.6 m rotation rates of 100 r.p.s. and heat flow rates of 10 kW would be required to achieve significant dynamo action. It is obvious that material strength and heat transfer problems will be the limiting factors for the success of such an experiment. Figure 3.9 shows a sketch of the experimental set up proposed by Lathrop.

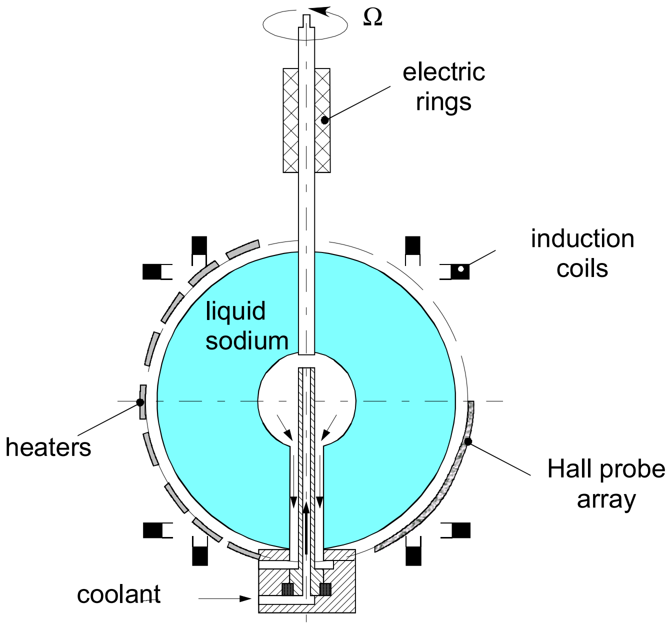

Figure 3.9. Experimental setup for a convection-driven dynamo experiment after Lathrop (2000).

4 Concluding remarks

Recently Albert Einstein was cited by Jackson (2000) in "NATURE" of saying that 'the Earth's magnetic field was one of the fundamental unsolved problems of physics'. During the last two decades the computer aided analysis of seismic and magneto-spherical data and the recent progress in computational fluid dynamics have greatly advanced our knowledge of the Earth's interior. The readily available computing capacities and the highly developed sodium technology - a spin off from nuclear reactor technology - have promoted on the one side the development of sophisticated physico-numerical geodynamo models and have stimulated on the other side efforts to explore and validate experimentally the generic mechanisms of homogeneous dynamos. There are still discrepancies in the scale up from so far obtainable numerical results to Earth's conditions, and only experiments on kinematic homogeneous dynamos have successfully been conducted so far. Nevertheless, one may be confident that most of the observed geomagnetic phenomena can be numerically simulated with the increasing capabilities of the next generation computers and that even convection driven dynamos will be realized in the laboratory in the future with the help of new high technology materials.

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