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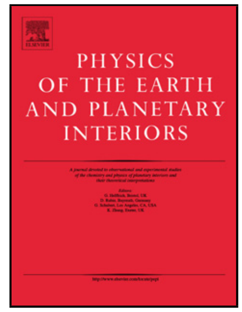

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Hydromagnetic dynamos in rotating non-uniformly stratified spherical fluid shells in dependence on the Rayleigh number

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Abstract

We present an investigation of dynamo in non-uniformly stratified spherical shells dependent on the Rayleigh number and thickness of a stable stratified sub-shell with emphasis on the case characterized by the identical thicknesses of both sub-shells. Our previous study of rotating convection showed that this case of stratification is a typical extreme case. However, the dynamo action in the shell characterized by the identical thicknesses of both sub-shells is not the typical extreme case. The generated magnetic field is close to the cases of uniform stratification and non-uniform one if the thickness of a stable stratified sub-shell is smaller than the thickness of an unstable stratified sub-shell. Similarly as in the case of rotating convection also in the case of dynamo action the multilayer convection ("teleconvection") is not developed in such a case because of the significant amount of stable stratification.

Key words:
Hydromagnetic dynamo, Non-uniform stratification, Penetrative convection, Rayleigh number

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1. Introduction

The dynamo theory, which is a significant part of cosmic magnetohydrodynamics, explains the generation mechanism and origin of the Earth's and planetary magnetic fields and their spatial and temporal evolution and changes (Roberts and Glatzmaier, 2000; Christensen and Wicht, 2007). Complicated processes going on in the Earth's and planetary fluid interiors, e.g., a chemical homogenisation, gravitational differentiation, solidification processes acting on the inner core boundary constitute the driving mechanism of dynamos, i.e. they are the fundamental source of convection or magnetoconvection (Jones, 2000). Non-uniform stratifications of the outer liquid Earth's core and the liquid interiors of Giant planets are a consequence of these processes (Fearn and Loper, 1981; Zhang and Schubert, 2000; Takehiro and Lister, 2001).

It is assumed that the upper part of the outer liquid Earth's core (close to the core-mantle boundary[1]) is stably stratified (subadiabatic radial temperature gradient) and the lower part (towards the inner core boundary[2]) unstably stratified (superadiabatic radial temperature gradient). Models of a non-uniformly stratified fluid shell present an acceptable simplification of the real Earth-like conditions. In the Earth's core the stably stratified sublayer is probably very thin (the outer Earth's core is almost unstably stratified, see Braginsky, 1964; Fearn and Loper, 1981; Zhang and Schubert, 2000; Šimkanin et al., 2003, 2006; Stanley and Mohammadi, 2008). A non-uniform stratification is probably typical for the terrestrial planets (Zhang and Schubert, 2000; Stanley and Bloxham, 2006; Stanley and Mohammadi, 2008). However, in the other planets the ratio of the thickness of the appropriate sublayers (e.g., of the stably stratified to unstably stratified sublayers) and their geometric configuration vary. This is noticeable especially with the Giant planets (Stanley and Bloxham, 2004, 2006; Zhang and Schubert, 2000; Stanley and Mohammadi, 2008). Let us briefly describe some examples where the geometric configuration plays an important role. Mercury is characterized by a weak magnetic field. A possible explanation could be given by a hydromagnetic dynamo working in the similar geometric configuration as supposed for the terrestrial planets (stable/unstable) but in this case a larger fraction of spherical shell is stably stratified (Christensen, 2006). In such a case the dynamo

[1] hereinafter referred to as CMB
[2] hereinafter referred to as ICB

runs in the small unstably stratified sublayer (close to ICB). Such a weak dynamo action and skin-effect (the magnetic field generated in the unstably stratified sublayer permeates through the stably stratified sublayer where it is damped due to skin-effect) lead to the weak magnetic field observed on the surface of Mercury (Christensen, 2006). For a different geometric configuration the influence of a non-uniform stratification is fundamental. Stanley and Bloxham (2004, 2006) assumed reverse stratification, i.e. the stably stratified sublayer is surrounded by the unstably stratified one. This configuration leads to non-dipolar and non-axisymmetric magnetic fields, which are typical e.g., for Uranus and Neptune (Stanley and Bloxham, 2004, 2006).

Non-uniform stratification can be simulated thermodynamically also in the Boussinesq models by means of internal heat sources (Zhang and Schubert, 2000; Šimkanin et al., 2003, 2006, 2010). If the stably stratified sublayer is very thin (for a geometric configuration stable/unstable), then behaviour is close to the case of uniform stratification when the whole layer is unstably stratified. Likewise, if the unstably stratified sublayer is very thin, then behaviour is close to the case of uniform stratification when the whole layer is stably stratified. Thus, the effects of non-uniform stratification are noticeable if the thicknesses of the stably and unstably stratified sublayers are comparable (Zhang and Schubert, 2000; Šimkanin et al., 2003, 2006, 2010).

In Šimkanin et al. (2010) we studied a convection in rotating non-uniformly stratified spherical fluid shells in dependence on the Ekman and Prandtl numbers, and the change of the sign of temperature gradient was located to the middle of the convective shell. The investigation provided the following main results. The multilayer convection ("teleconvection") did not develope in our case of non-uniform stratification because of the significant amount of stable stratification. The case characterized by the identical thicknesses of both sublayers presents a typical extreme case. It is dissimilar to the case where the stably stratified sublayer is thinner than the unstably stratified one and also dissimilar to the case where the unstably stratified sublayer is thinner than the stably stratified one. In the present paper we study the influence of magnetic field to our model, i.e. a dynamo action in the non-uniformly stratified spherical fluid shell in dependence on the Rayleigh number and thickness of a stable stratified sub-shell with emphasis on the case characterized by the identical thicknesses of both sublayers.

The model and governing equations are given in Section 2. The numerical results are presented in Section 3. Finally, Section 4 provides the conclusions.

2. Governing equations and model

Here we consider dynamo action due to thermal convection of an electrically conducting incompressible fluid in the Boussinesq approximation in a non-uniformly stratified spherical shell ($r_i < r < r_o$) rotating with angular velocity Ω. The evolution of the magnetic field $\mathbf{B}$, the velocity $\mathbf{V}$ and the temperature T is described by the following system of dimensionless equations:

$$E\left(\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V}\cdot\nabla)\,\mathbf{V} - \nabla^2\mathbf{V}\right) + 2\mathbf{1}_z \times \mathbf{V} + \nabla P = R_a \frac{\mathbf{r}}{r_o} T + \\ + \frac{1}{P_m}(\nabla \times \mathbf{B}) \times \mathbf{B}, \tag{1}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B}) + \frac{1}{P_m}\nabla^2\mathbf{B}, \tag{2}$$

$$\frac{\partial T}{\partial t} + (\mathbf{V}\cdot\nabla)\,T = \frac{1}{P_r}\nabla^2 T + H, \tag{3}$$

$$\nabla\cdot\mathbf{V} = 0, \quad \nabla\cdot\mathbf{B} = 0. \tag{4}$$

The radius of the outer sphere L, is the typical length scale, which makes the dimensionless radius $r_o = 1$; the inner core radius r_i is, similar to that of the Earth, equal to 0.35. (r, θ, φ) is the spherical system of coordinates, $\mathbf{1}_z$ is the unit vector. The typical time, t, is measured in the unit of L^2/ν, typical velocity, $\mathbf{V}$, in ν/L, typical magnetic induction, $\mathbf{B}$, in $(\rho\mu\eta\Omega)^{1/2}$, typical temperature, T, in ΔT, and pressure, P, in $\rho\nu^2/L^2$. The dimensionless parameters appearing in Eqs (1)-(4) are the Prandtl number, $P_r = \nu/\kappa$, the magnetic Prandtl number, $P_m = \nu/\eta$, the Ekman number, $E = \nu/\Omega L^2$ and the modified Rayleigh number $R_a = \alpha g_0 \Delta T L/\nu\Omega$, where κ is the thermal diffusivity, ν is the kinematic viscosity, μ is the magnetic permeability, η is the magnetic diffusivity, ρ is the density, α is the coefficient of thermal expansion, ΔT is the drop of temperature through the shell and g_0 is the gravity acceleration at $r = r_o$.

Eqs (1)-(4) are closed by the non-penetrating and no-slip boundary conditions for the velocity field at the rigid surfaces and fixed temperature boundary conditions. The regions outside the fluid shell are electrical insulators (the magnetic field on the boundaries matches with appropriate potential fields in the exterior that imply no external sources of the field).

The last term in Eq. (3), H, constitutes the internal heat sources (it is the non-dimensional volumetric heat source strength), which enables simulating thermodynamically the various stratification of the spherical shells also in the Boussinesq models. The outer sphere was assumed to be stratified non-uniformly (it is divided into stably and unstably stratified sub-shells) with constant temperature $T_i = 1$ and $T_o = 0$ at the inner and outer boundaries of the shell, respectively. The width of both sub-shells was considered to be the same (we denote this case NON-UNI 50), i.e. $\partial T/\partial r$ changes its sign in the middle of the convective shell, $r_m = (r_i + r_o)/2$. It is accomplished if $H = -23P_r^{-1}$. Let us describe why we used this value. The non-uniform stratification is considered due to internal heat sources and in the basic state Eq.(3) gets the form

$$\frac{1}{P_r}\nabla^2 T + H = 0. \quad (5)$$

If we solve Eq. (5) considering $T_i = 1$, $T_o = 0$ and $\partial T/\partial r = 0$ at $r = r_m$, we obtain $H = -23P_r^{-1}$. It is necessary to remark that for the uniform stratification $H = 0$. In order to compare the case NON-UNI 50 to cases in which is the ratio of stable to unstable stratified sub-shells different, we study gradually cases where 5% (denoted NON-UNI 5), 25% (denoted NON-UNI 25), 75% (denoted NON-UNI 75) and 95% (denoted NON-UNI 95) of the shell is stably stratified.

3. Numerical results

Eqs (1)-(4) were solved using the MAG dynamo code (Olson and Glatzmaier, 1995, 1996; Olson et al., 1999; Christensen et al., 1999, 2001; Olson and Glatzmaier, 2005; Christensen and Aubert, 2006). It is a serial version of Gary Glatzmaier's rotating spherical convection/magnetoconvection/dynamo code, modified by Ulrich Christensen and Peter Olson. The code solves the non-dimensional Boussinesq equations for time-dependent thermal convection in a rotating spherical shell filled with an electrically conducting fluid. MAG uses toroidal-poloidal decomposition for velocity and magnetic field with explicit time steps. Linear terms are evaluated spectrally (spherical harmonics plus Chebyshev polynomials in radius) and nonlinear terms are evaluated on a spherical grid (for more details, see Olson and Glatzmaier, 1995, 1996; Olson et al., 1999; Christensen et al., 1999, 2001; Olson and Glatzmaier, 2005). The computations were performed on the Sun Grid Engine (LUNA) at the Institute of Physics, Academy of Sciences of CR, Prague, and the Nemo cluster (SGI) at the Institute of Geophysics, Academy of Sciences of CR, Prague.

The dependence of solutions on various values of the Rayleigh number, R_a, for the given Prandtl number, P_r, magnetic Prandtl number, P_m, and Ekman number, E, was investigated. Computations started from zero initial velocity and strong dipole-dominated field with $B \sim \mathcal{O}(1)$, and were performed for $P_r = 1$, $E = 10^{-4}$, $P_m = 2$, and $R_a = 550, 650, 800, 900, 1000$. In the case of non-uniform stratification $H = -2.41$ (NON-UNI 5), $H = -4.60$ (NON-UNI 25), $H = -23$ (NON-UNI 50), $H = 15.9$ (NON-UNI 75) and $H = 8.96$ (NON-UNI 95) as $P_r = 1$ and in the case of uniform one, $H = 0$ (in this case the whole shell is unstably stratified).

For $P_r = 1$, the characteristic thermal diffusion time is equal to the characteristic viscous diffusion time ($\tau_\kappa = \tau_\nu$), i.e. thermal and viscous diffusion processes affect equally the dynamics of convection and dynamo. The dependences of the mean kinetic energy, E_k, and the mean magnetic energy, E_m, on R_a and the type of stratification (uniform and non-uniform) are given in Fig. 1. E_k increases for given E, P_r and P_m with increasing of R_a and for a given R_a it is greater in the cases of non-uniform stratification than in the case of uniform one. E_k increases for a given R_a also with increasing of the thickness of a stable stratified sub-shell, except the case NON-UNI 95 when it decreases comparing to the case NON-UNI 75 (see Fig. 1). E_m also increases for a given E, P_r and P_m with increasing of R_a, and for a given R_a, it is greater in the case of uniform stratification than in the cases of non-uniform one. E_m decreases for a given R_a with increasing of the thickness of a stable stratified sub-shell, even in the case NON-UNI 95 the dynamo fails for $t > 10$ (see Fig. 1). Thus, the dependences of E_k and E_m on the type of stratification are strong.

The typical space distributions of the radial magnetic field component, B_r are presented in Fig. 2, the radial velocity field component, V_r in Fig. 3, and, finally, the typical space distributions of the complete magnetic field $\mathbf{B}$ at CMB are presented in Fig. 4. All the figures are snapshots done at time $t = 10$ (10 time units). Fig. 2 and 3 were done using the value of $r = 0.65$, which lies in the case NON-UNI 50 in the unstable region but close to the interface $r = r_m$ ($r_m = 0.675$). We used this value in order to compare magnetic and velocity fields in the same region for different thicknesses of stable stratified sub-shells. However, Fig. 4 was done using $r = r_o$ (at CMB).

The generated magnetic field is dipolar in all investigated cases except the cases NON-UNI 75 and NON-UNI 95 when it is non-dipolar, even for

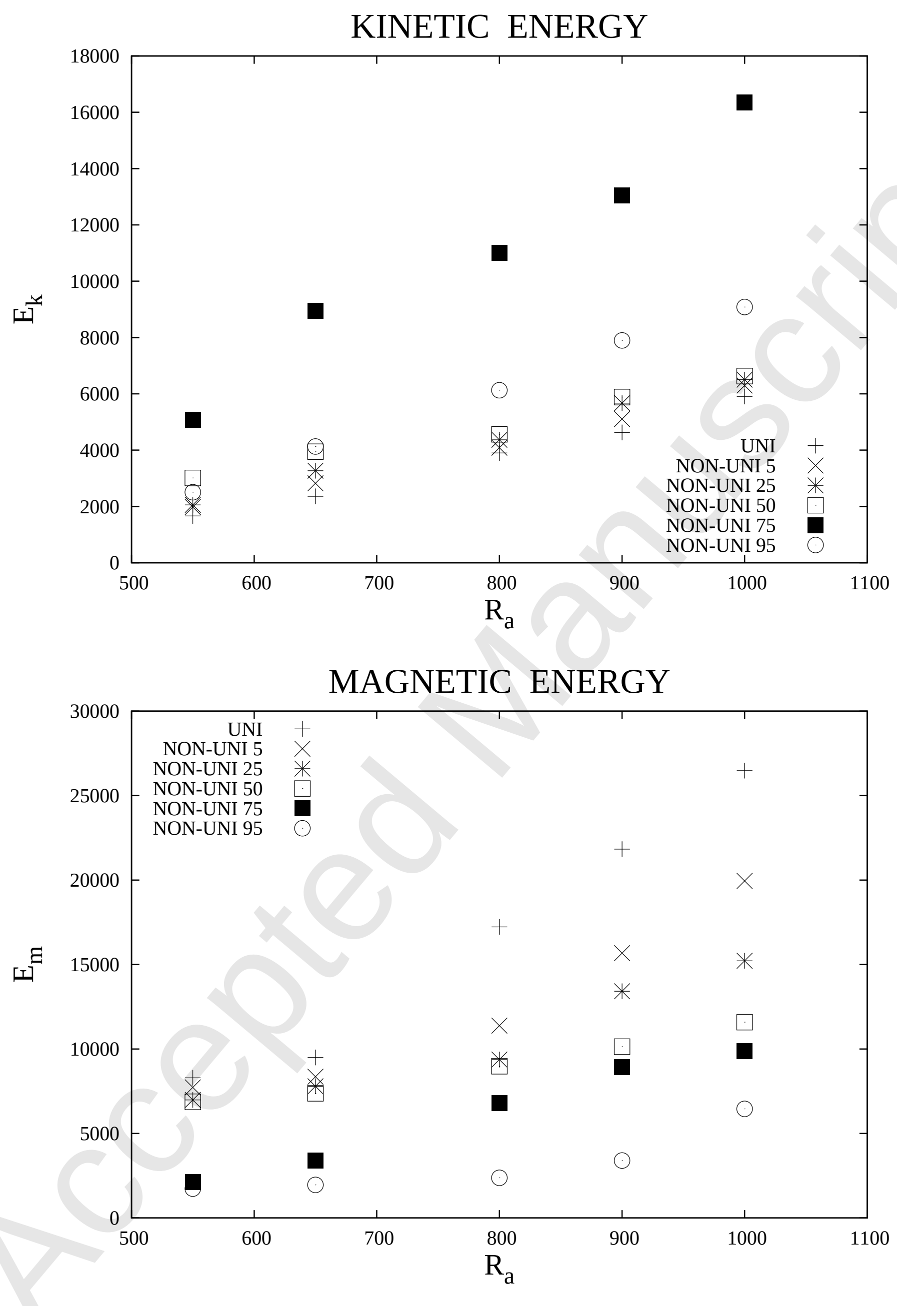

Figure 1: Dependences of the mean kinetic energy, E_k, (top) and the mean magnetic energy, E_m, (bottom) on the Rayleigh number, R_a, and the type of stratification (uniform - UNI and non-uniform - NON-UNI 5,25,50,75,95) for $E = 10^{-4}$, $P_r = 1$ and $P_m = 2$.

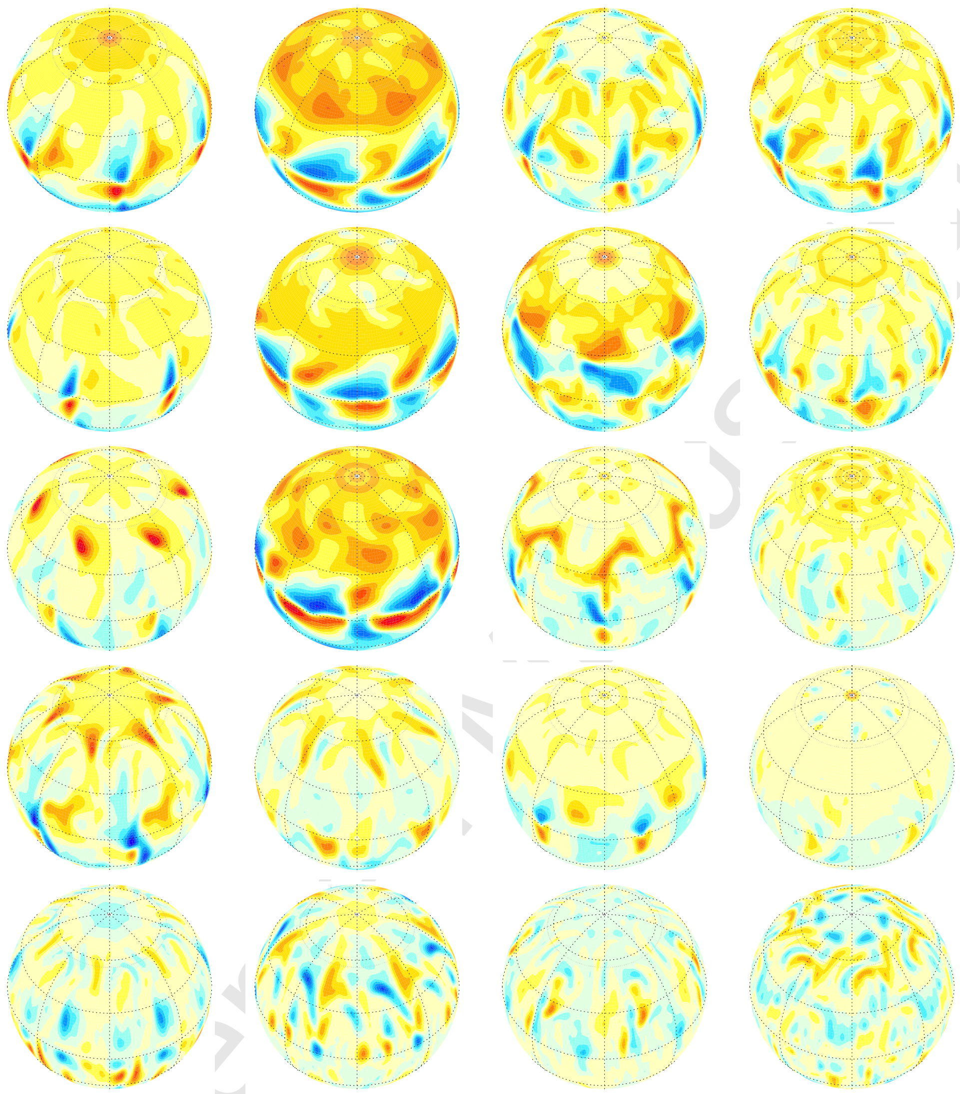

Figure 2: Space distributions of radial magnetic field components B_r at $r = 0.65$ for $R_a = 550, 650, 800, 900$ (from left to right), for for the cases of uniform stratification, NON-UNI 5, NON-UNI 25, NON-UNI 50 and NON-UNI 75 (from top to bottom), and for $E = 10^{-4}$, $P_r = 1$ and $P_m = 2$. Red (blue) colours indicate positive (negative) values. Minimal and maximal values for the first row are (-4.9, 4.9), (-8.6, 8.6), (-10, 10), (-12, 12), for the second row (-5.7, 5.7), (-8.3, 8.3), (-11, 11), (-8.0, 8.0), for the third row (-6.9, 6.9), (-5.7, 5.7), (-9.1, 9.1), (-10, 10), for the fourth row (-5.1, 5.1), (-9.2, 9.2), (-8.8, 8.8), (-12, 12) and for the fifth row (-3.0, 3.0), (-3.1, 3.1), (-8.5, 8.5), (-6.2, 6.2). Snapshots at $t = 10$.

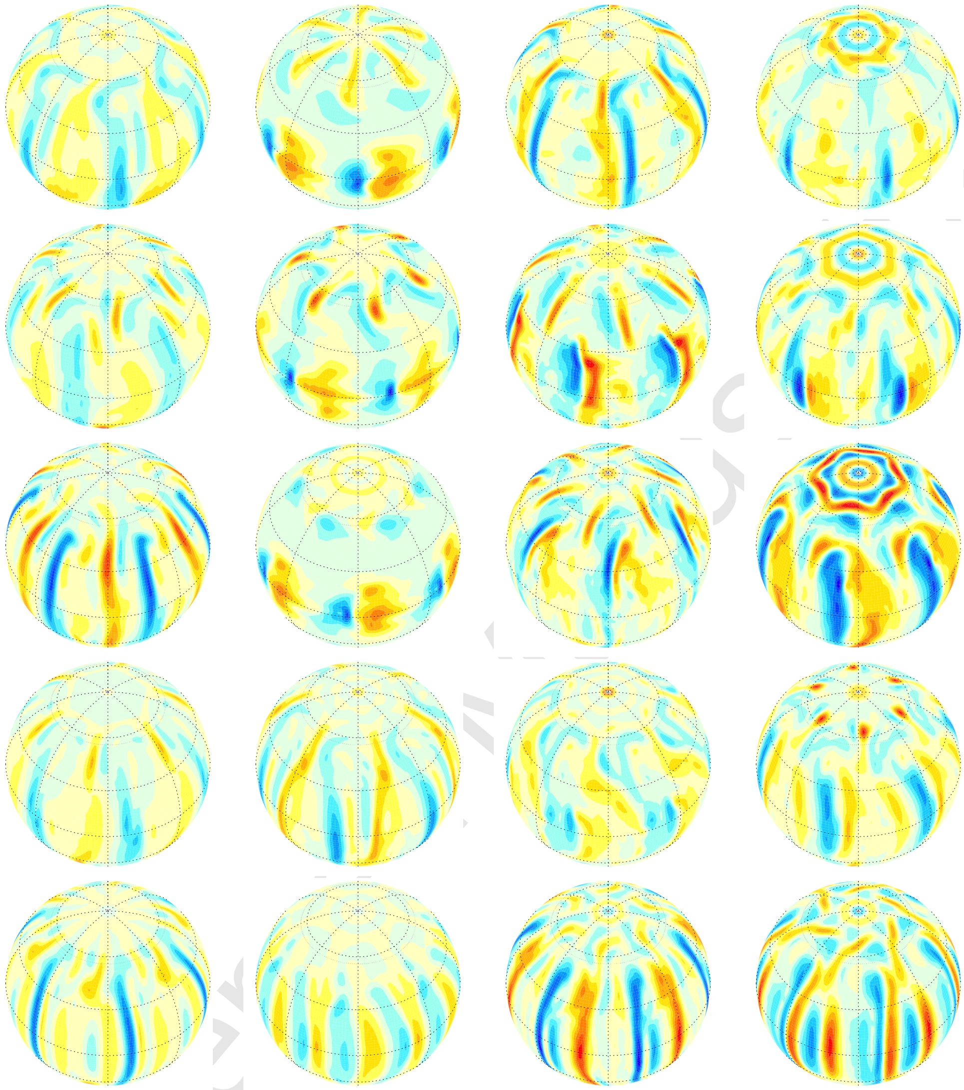

Figure 3: Space distributions of radial velocity field components V_r at $r = 0.65$ for $R_a = 550, 650, 800, 900$ (from left to right), for for the cases of uniform stratification, NON-UNI 5, NON-UNI 25, NON-UNI 50 and NON-UNI 75 (from top to bottom), and for $E = 10^{-4}$, $P_r = 1$ and $P_m = 2$. Red (blue) colours indicate positive (negative) values. Minimal and maximal values for the first row are (-165, 165), (-123, 123), (-291, 291), (-276, 276), for the second row (-185, 185), (-128, 128), (-171, 171), (-232, 232), for the third row (-158, 158), (-119, 119), (-251, 251), (-228, 228), for the fourth row (-323, 323), (-250, 250), (-197, 197), (-276, 276) and for the fifth row (-286, 286), (-397, 397), (-366, 366), (-387, 387). Snapshots at $t = 10$.

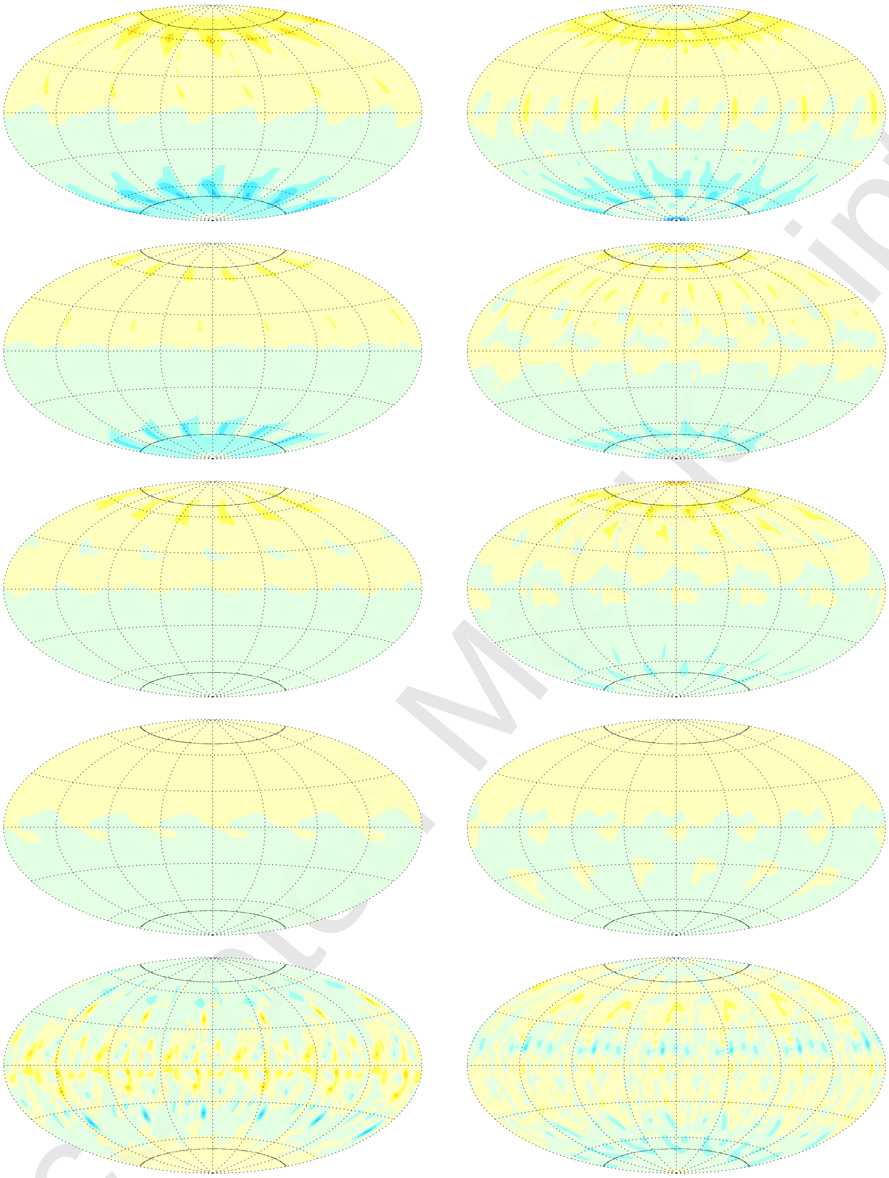

Figure 4: The complete magnetic field at the outer surface of the shell (at $r = r_o$) for $R_a = 550$ (left column) and $R_a = 900$ (right column), for for the cases of uniform stratification, NON-UNI 5, NON-UNI 25, NON-UNI 50 and NON-UNI 75 (from top to bottom), and for $E = 10^{-4}$, $P_r = 1$ and $P_m = 2$. Red (blue) colours indicate positive (negative) values. Minimal and maximal values for the first row are (-7.3, 7.3), (-17, 17), for the second row (-8.5, 8.5), (-13, 13), for the third row (-11, 11), (-16, 16), for the fourth row (-7.6, 7.6), (-17, 17) and for the fifth row (-4.4, 4.4), (-9.3, 9.3). Snapshots at $t = 10$.

the NON-UNI 95 a dynamo fails (see Figs. (2,4) but the case NON-UNI 95 is not presented because of failed dynamo). The strong antisymmetric character of magnetic field about the equator (a typical feature of the dipole dominated magnetic fields) is visible in the case of uniform stratification and if the thickness of a stable stratified sub-shell is smaller/equal than/to the thickness of an unstable stratified sub-shell (see Figs. (2,4)). Increasing the value of R_a small-scale structures are more visible.

The symmetric character of the velocity field about the equator and the spiralling cross section of the columns are typical features for both cases of stratification (see Fig. 3). For low values of R_a in the case of uniform stratification, a large-scale columnar convection is developed in the whole volume, while in the case of non-uniform stratification it is shifted out of CMB (suppressed to the unstably stratified region) but penetrates to the stably stratified one. A measure of such a penetration is governed by the value of the Brunt-Väisälä frequency (e.g. Takehiro and Lister, 2001, 2002). Increasing the thickness of a stable stratified sub-shell such a shifting becomes stronger (the convection is more and more suppressed to the unstably stratified region and less and less penetrates to the stably stratified region). In addition, increasing the thickness of a stable stratified sub-shell it is possible to observe a rise in the breakdown of the columnar character of the convection (see Fig. 3). A columnar structure of the convection is believed to be important in the generation of strong dipolar magnetic fields (Olson et al., 1999; Christensen and Aubert, 2006; Christensen and Wicht, 2007). Increasing R_a the small scales become important but the convection is still columnar. It is possible to observe in the stably stratified sub-shell a weak tendency of flow to be more toroidal.

The radial stratification causes the toroidal motions in the outermost part of the shell ("teleconvection"). It cannot take place without such a radial stratification and is possible if the unstable stratification dominates over the stable one (Zhang and Schubert, 2000; Busse and Simitev, 2005; Šimkanin et al., 2010). The multilayer convection ("teleconvection") is developed only in the cases NON-UNI 5 and NON-UNI 25 and is more visible for larger values of R_a (see Fig. 3, especially the case NON-UNI 25 for $R_a = 900$). However, the multilayer convection ("teleconvection") is not developed in the cases NON-UNI 50, NON-UNI 75 and NON-UNI 95 because of the significant amount of stable stratification (see Fig. 3).

4. Conclusions

Density stratification plays a significant role in the astrophysical and geophysical processes. It is an important dynamic factor in the processes acting in planetary atmospheres (e.g., Heimpel et al., 2005), planetary interiors (e.g., Braginsky, 1964; Stanley and Bloxham, 2004, 2006; Zhang and Schubert, 2000; Stanley and Mohammadi, 2008; Christensen, 2006; Šimkanin et al., 2003, 2006), etc. Systematical parameter studies of rotating convection and dynamo in uniformly and non-uniformly stratified spherical shells were done in many previous studies (e.g., Zhang and Schubert, 2000; Takehiro and Lister, 2001, 2002; Stanley and Bloxham, 2004, 2006; Stanley and Mohammadi, 2008; Christensen, 2006; Christensen and Wicht, 2008). However, our attention is focused on the case when the thickness of both sublayers (stable and unstable) is the same. It is true that neither planet nor satellite with this geometric configuration has been observed. Nevertheless, it is interesting to investigate such a case in order to answer a question whether its behaviour is closer to the case of a stable stratification or an unstable one.

We investigated in Šimkanin et al. (2010) a convection in rotating non-uniformly stratified spherical fluid shells in dependence on the Ekman and Prandtl numbers, and the change of the sign of temperature gradient was located to the middle of the convective shell. The investigations provided the following main results. The multilayer convection ("teleconvection") is not developed in our case of non-uniform stratification, because of the significant amount of stable stratification. The case characterized by the identical thicknesses of both sublayers is a typical extreme case. It is dissimilar to the case where the stably stratified sublayer is thinner than the unstably stratified one (although the convection penetrates to the stably stratified sublayer, it is more suppressed to the unstably stratified sublayer than in the case of thinner stably stratified sublayer) and also dissimilar to the case where the unstably stratified sublayer is thinner than the stably stratified one (although the convection is significantly suppressed to the unstably stratified sublayer, still penetrates to the stably stratified sublayer more than in the case of thinner unstably stratified sublayer). The Prandtl number was the most significant dynamic factor (for more details, see Šimkanin et al., 2010).

In the present paper we continue with a study of a dynamo action. In order to compare the case NON-UNI 50 to cases in which is the ratio of stable to unstable stratified sub-shells different, we gradually studied the case of uniform stratification and then cases of non-uniform stratification increasing the thickness of a stable stratified sub-shell in dependence on the Rayleigh number. The results showed that generated magnetic fields are in cases UNI, NON-UNI 5, NON-UNI 25 and NON-UNI 50 dipolar, in the case NON-UNI 75 non-dipolar and in the case NON-UNI 95 the dynamo failed. Magnetic fields become weak with increase of the thickness of a stable stratified sub-shell (the dipolar magnetic field in the case NON-UNI 50 is weaker than in the case NON-UNI 5 but it is stronger than the non-dipolar magnetic field in the case NON-UNI 75) because the stably stratified sublayer acts to destabilize the dynamo (Stanley and Mohammadi, 2008). Let us compare the results of Christensen (2006); Christensen and Wicht (2008) with our results. In their models 60% of the shell is stably stratified (it could be the case "NON-UNI 60" in our denotation). In such a case the dynamo action is strongly suppressed in the upper stably stratified sublayer, i.e. the dynamo runs in the small unstably stratified sublayer (close to ICB). Such weak dynamo action and skin-effect (the magnetic field generated in the unstably stratified sublayer permeates through the stably stratified sublayer where it is damped due to skin-effect) lead to the weak magnetic field observed on the surface of Mercury (Christensen, 2006). A large-scale columnar convection is in the case of non-uniform stratification shifted out of CMB (suppressed to the unstably stratified region) but penetrates to the stably stratified one. The measure of such a penetration is governed by the value of the Brunt-Väisälä frequency (e.g. Takehiro and Lister, 2001, 2002). From this point of view a stratified layer acts as a filter of the convection. Increasing the thickness of a stable stratified sub-shell such a shifting becomes strong. Increasing R_a the small scales become important but the convection is still columnar. It is possible to observe in the stably stratified sub-shell a weak tendency of flow to be more toroidal. The multilayer convection ("teleconvection") is developed only in the cases NON-UNI 5 and NON-UNI 25 but it is not developed in the cases NON-UNI 50, NON-UNI 75 and NON-UNI 95 because of the significant amount of stable stratification.

Our results support previous analyses done in the uniformly or non-uniformly stratified spherical shells (e.g., Zhang and Schubert, 2000; Takehiro and Lister, 2001, 2002; Šimkanin et al., 2003, 2006; Busse and Simitev, 2005; Christensen, 2006; Christensen and Wicht, 2007, 2008; Stanley and Bloxham, 2004, 2006; Stanley and Mohammadi, 2008). In Šimkanin et al. (2010), the rotating convection, the results showed that the case characterized by the identical thicknesses of both sublayers is a typical extreme case. However, the dynamo action in the shell characterized by the identical thicknesses of both sublayers (NON-UNI 50) is not the typical extreme case. The generated magnetic field is close to the cases of uniform stratification and non-uniform one if the thickness of a stable stratified sub-shell is smaller than the thickness of an unstable stratified sub-shell. From this point of view, the case "NON-UNI 60" described in Christensen (2006); Christensen and Wicht (2008) could be an extreme case because it separates two different dynamos (dipolar (NON-UNI 50) / non-dipolar (NON-UNI 75)).

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