Dynamics of Rotating Fluids

Equations of motion

$$\left(\frac{\partial}{\partial t} + \mathbf{u}\cdot\nabla\right)\mathbf{u} + \underline{2\boldsymbol{\Omega}\times\mathbf{u}} = \underline{-\nabla\pi} + \nu\nabla^2\mathbf{u}$$

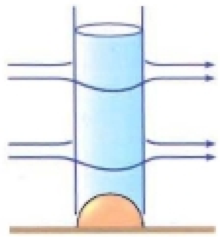
$$\nabla\cdot\mathbf{u} = 0$$

$$\nabla\times(2\boldsymbol{\Omega}\times\mathbf{u}) = 2\boldsymbol{\Omega}\nabla\cdot\mathbf{u} - 2\boldsymbol{\Omega}\cdot\nabla\mathbf{u} = 0$$

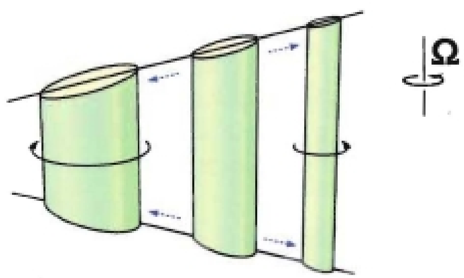
Proudman-Taylor-theorem

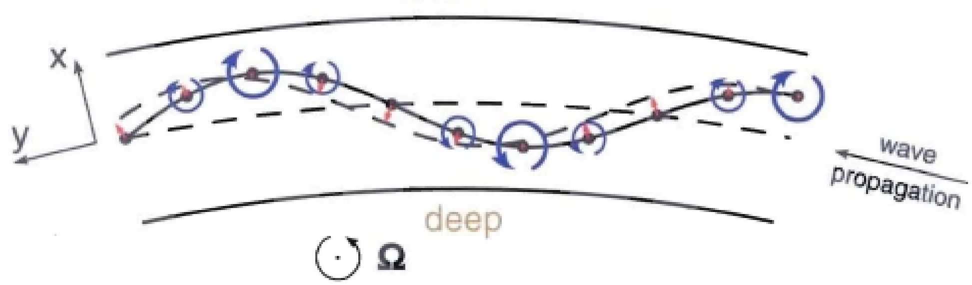
$$\boldsymbol{\Omega}\cdot\nabla\mathbf{u} = 0$$

Taylor column



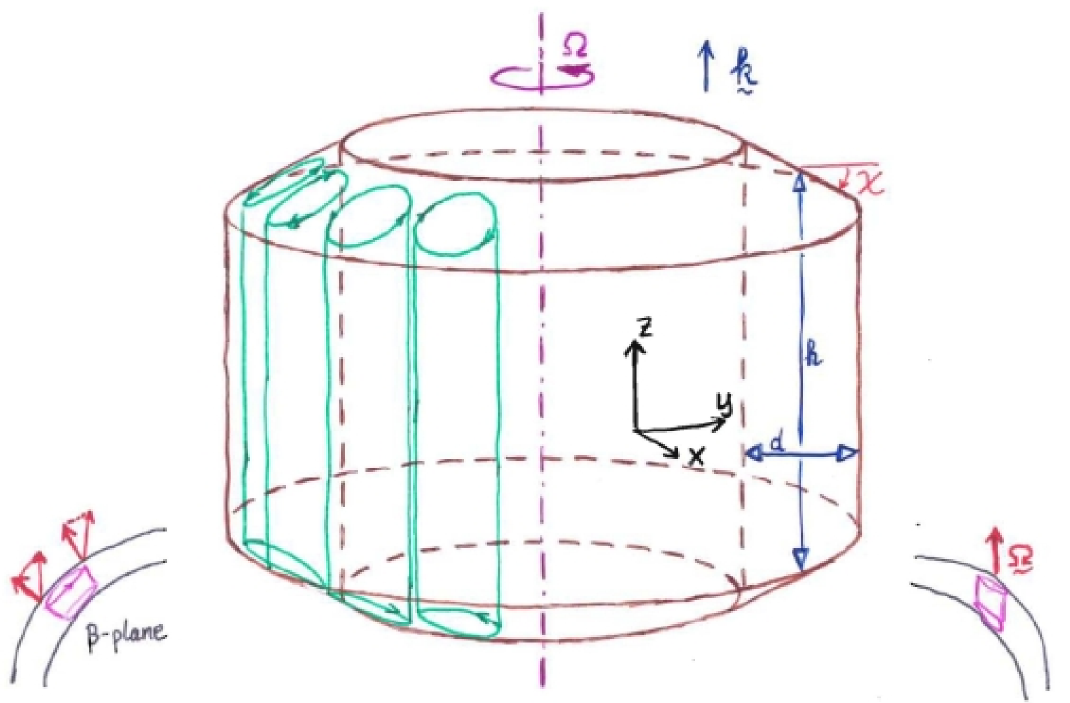
Rossby waves





for $u \propto \exp\{\, i\alpha y + i\omega t \,\}\, \cos\gamma x$

$$\omega = -\frac{2\,\Omega\,\alpha\,\eta}{\alpha^2+\gamma^2}$$



Rossby Waves in the Rotating Cylindrical Annulus

$\underset{\sim}{k}\cdot\nabla\times\ldots$

$$\frac{\partial}{\partial t}\underset{\sim}{u} + 2\underset{\sim}{\Omega}\times\underset{\sim}{u} = -\nabla\pi$$

$$\nabla\cdot\underset{\sim}{u} = 0$$

$$\underset{\sim}{u} = \nabla\psi(x,y)\times\underset{\sim}{k}\, e^{i\omega t} + \ldots$$

$\frac{1}{h}\int_{-\frac{h}{2}}^{\frac{h}{2}}\ldots dz$

$$-i\omega\Delta_2\psi - 2\Omega\,\underset{\sim}{k}\cdot\nabla u_z = 0$$

$\Delta_2 \equiv \frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}$

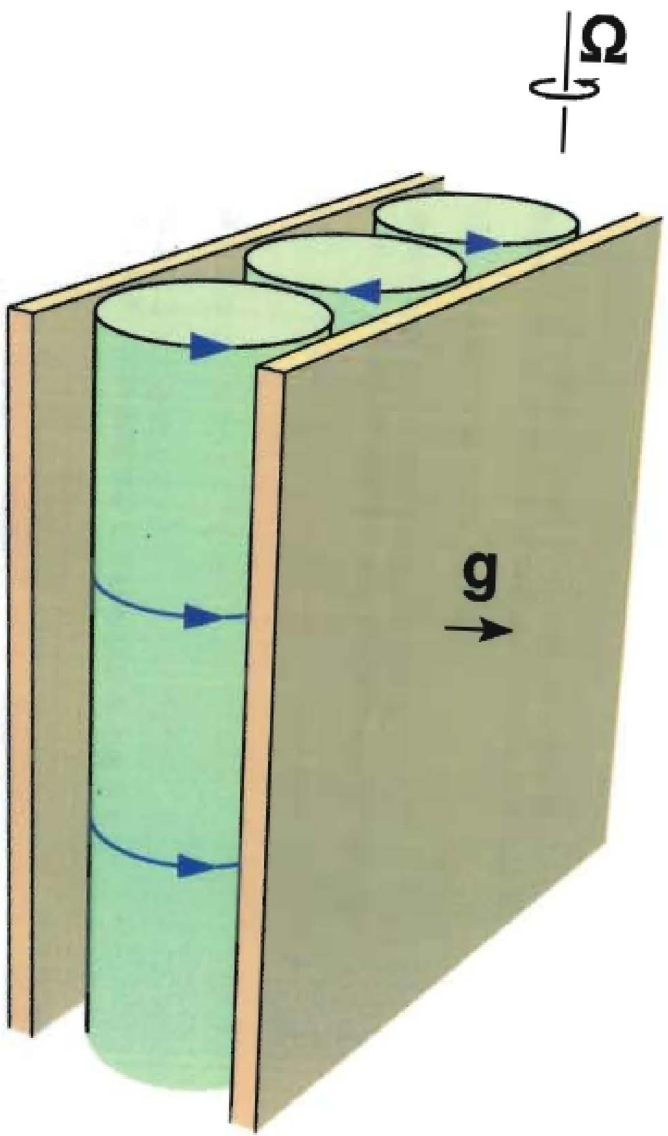
$\eta_0 = \tan\chi$

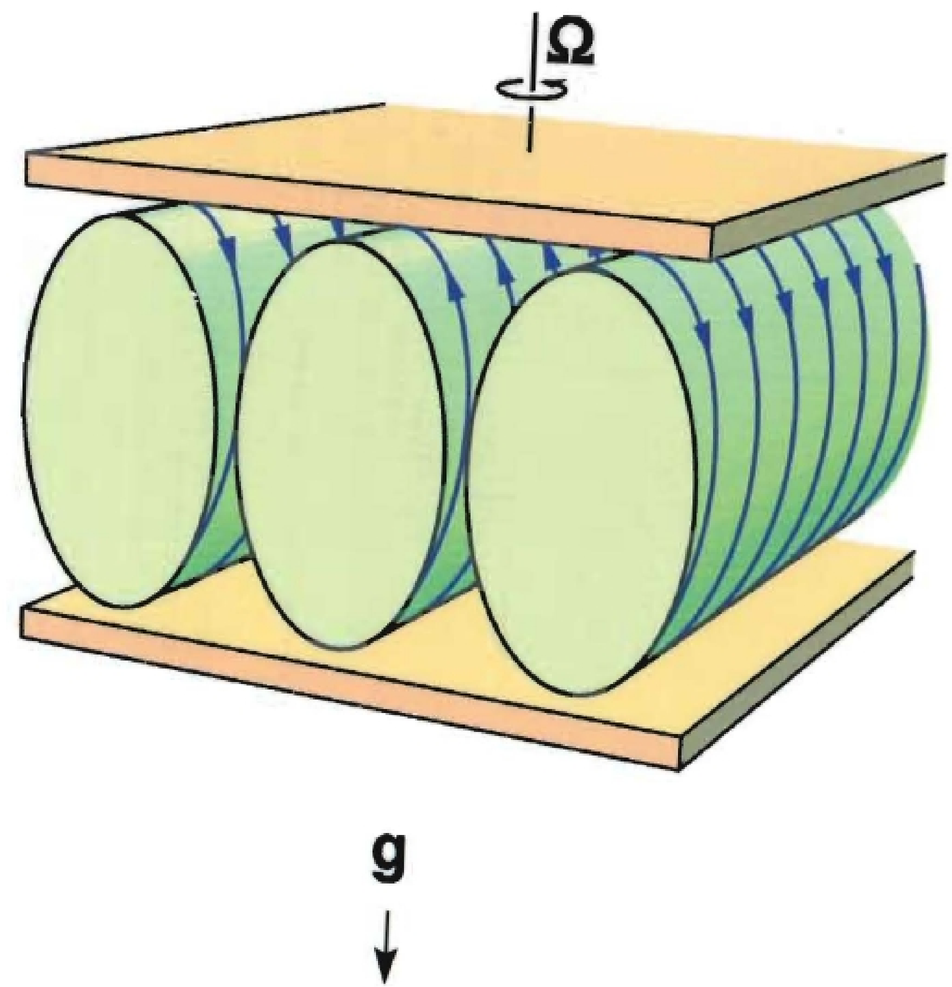
$u_z \pm \eta_0\frac{\partial}{\partial y}\psi = 0$ at $z = \pm\frac{h}{2}$

$$-i\omega\Delta_2\psi + \frac{4\Omega}{h}\eta_0\frac{\partial}{\partial y}\psi = 0$$

$$\psi(x,y) = \cos\frac{\pi}{d}x\,\exp\{i\alpha y\}$$

$$\omega = -\frac{4\eta_0\Omega\alpha}{h\left(\frac{\pi^2}{d^2}+\alpha^2\right)}$$


Ω
g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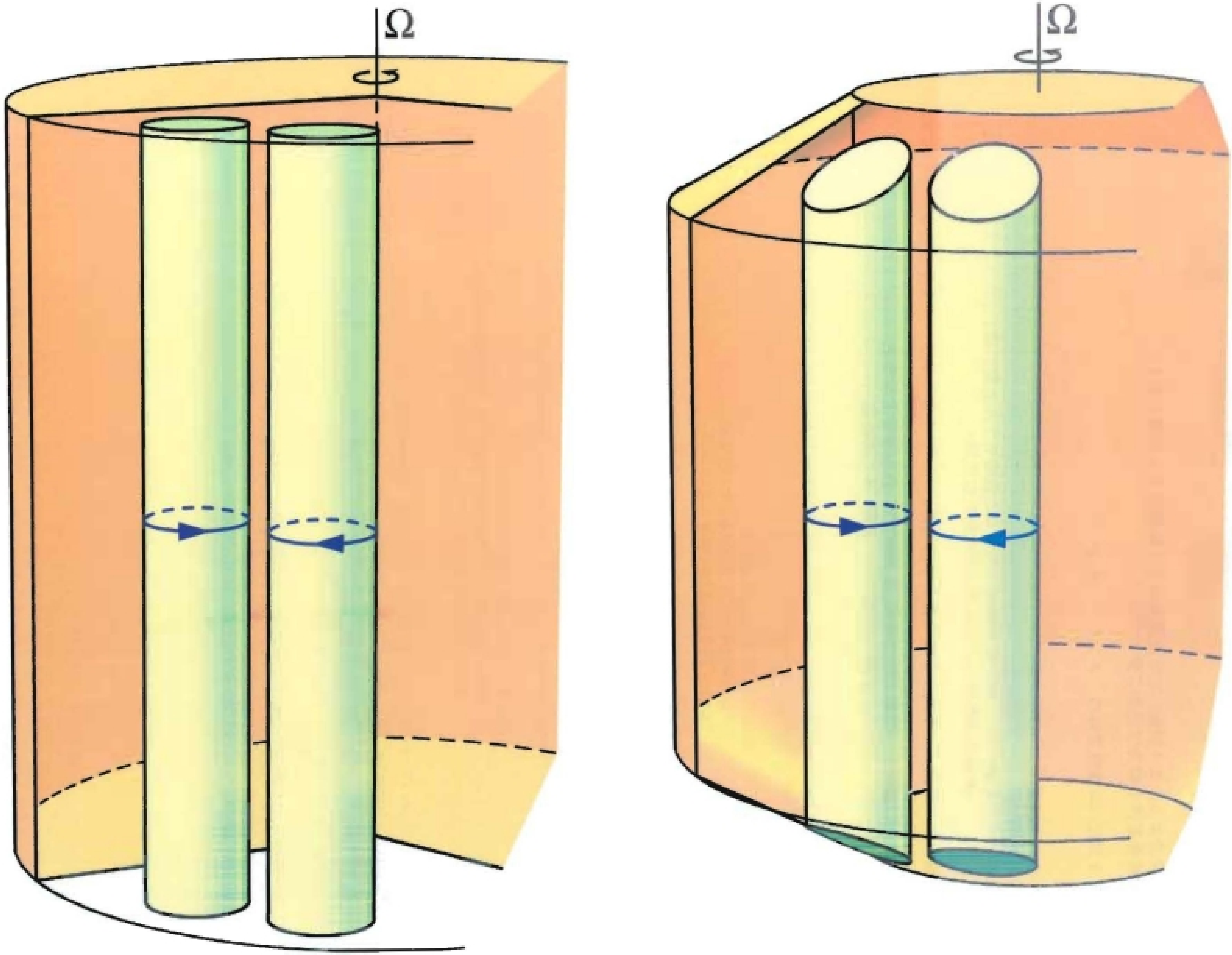
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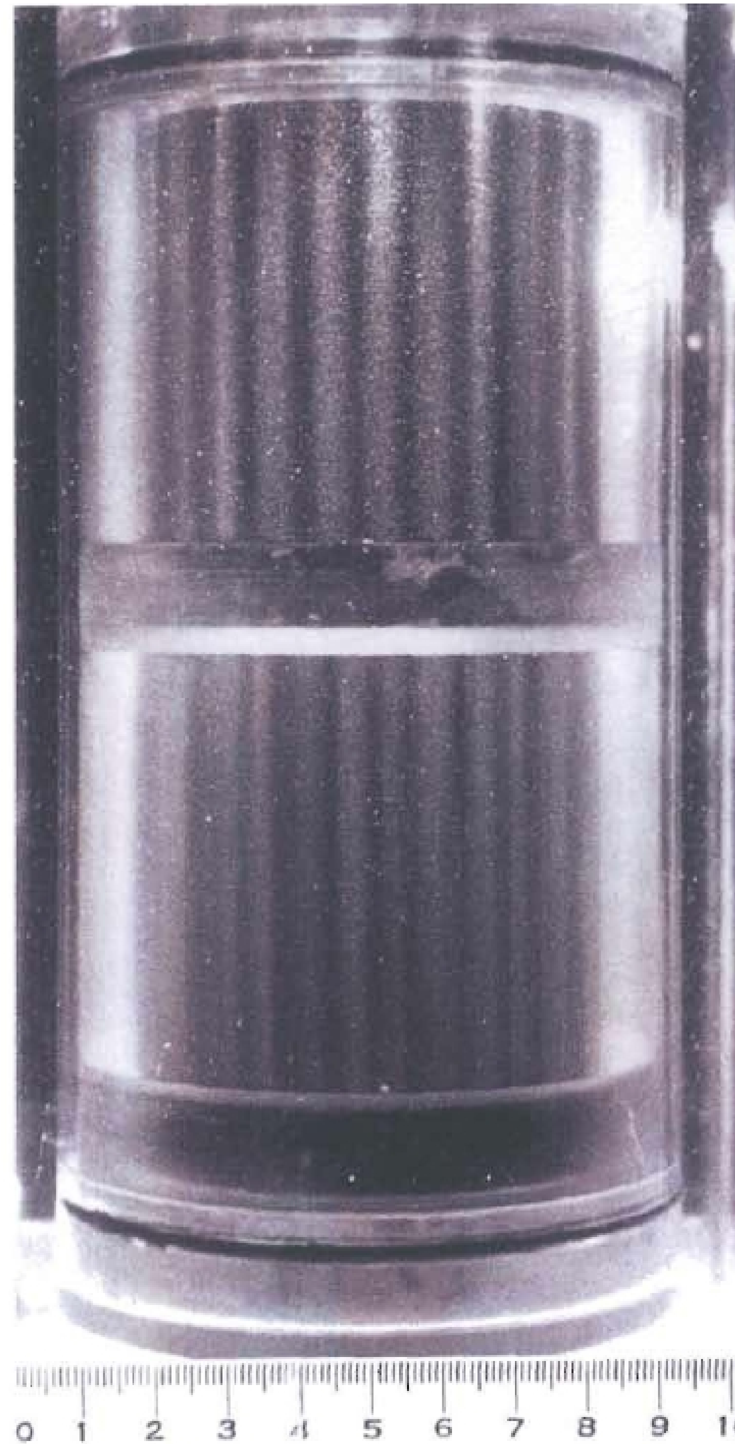
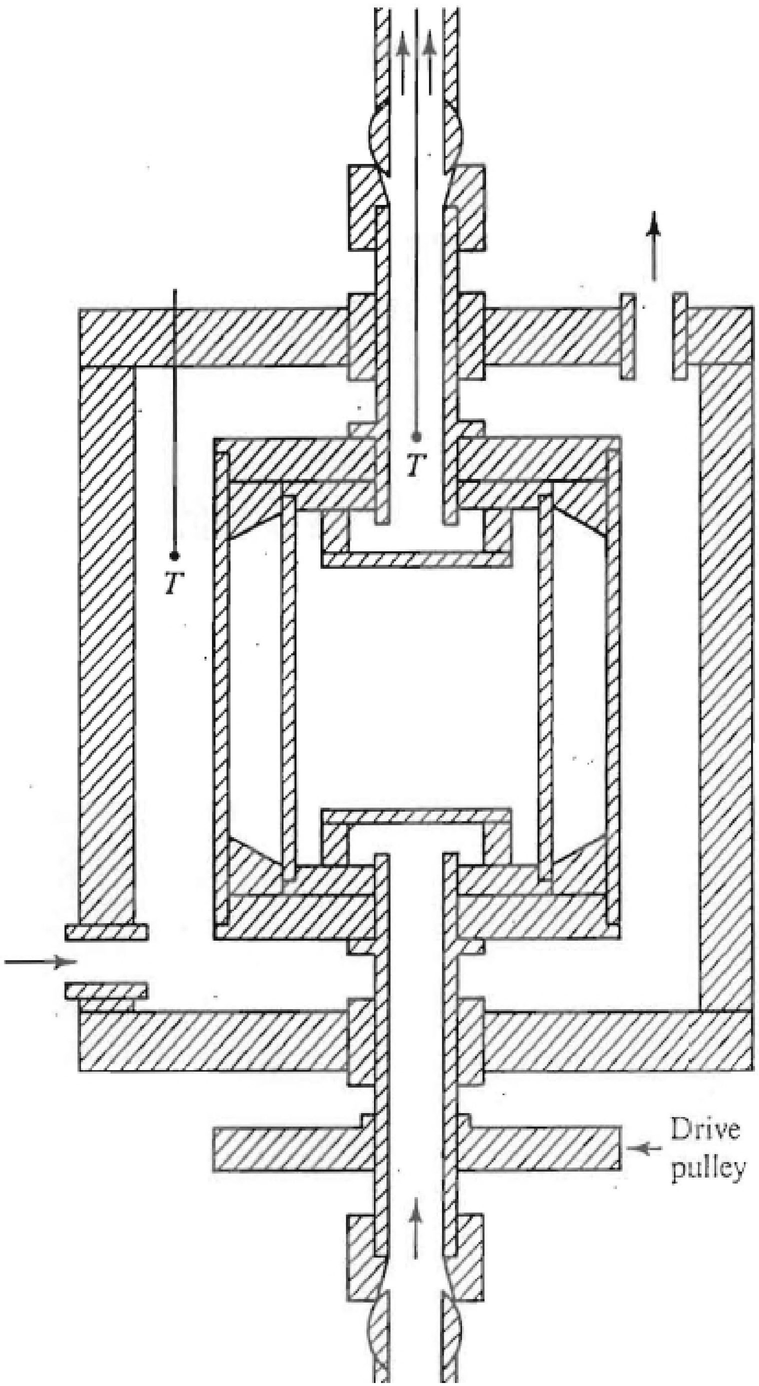
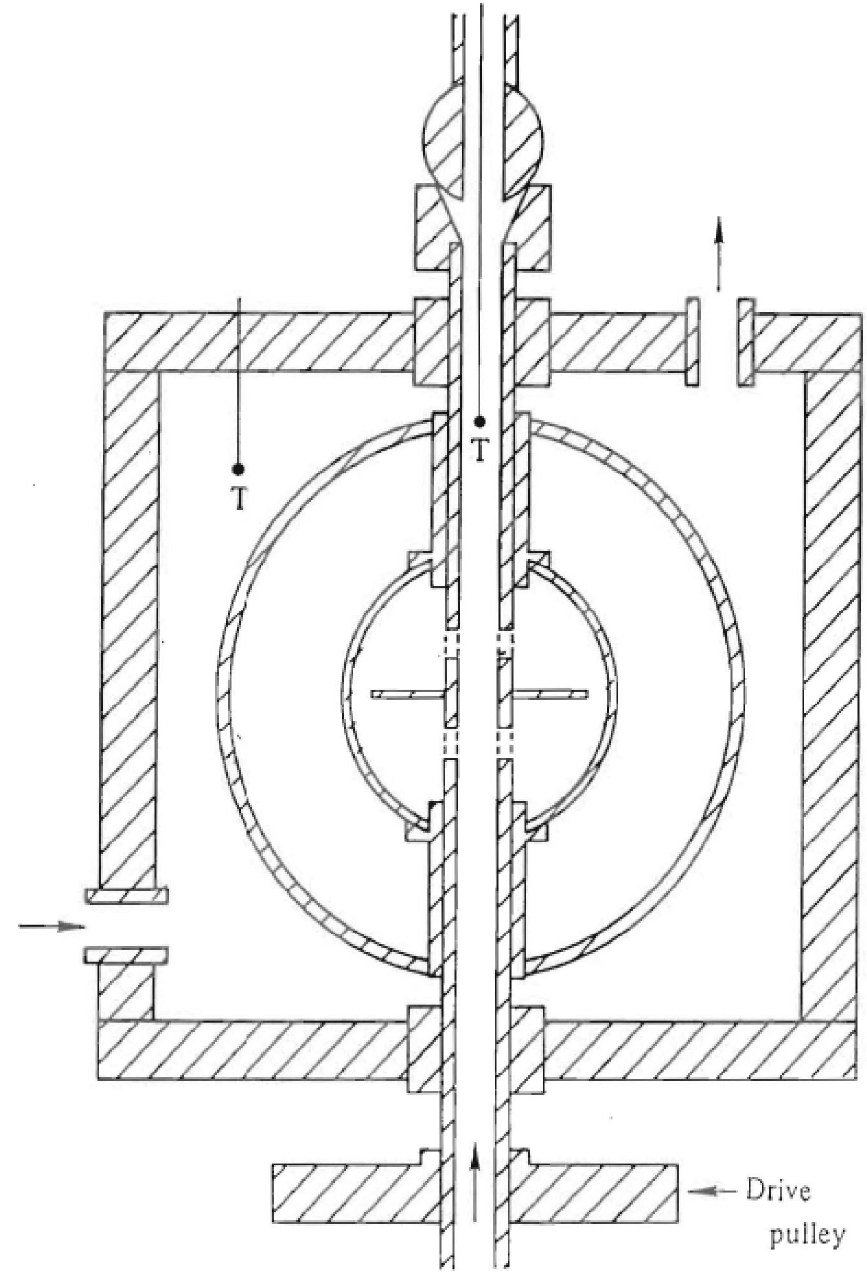
0 1 2 3 4 5 6 7 8 9 10

0 1 2 3 4 5 6 7 8 9 10


T
T
Drive
pulley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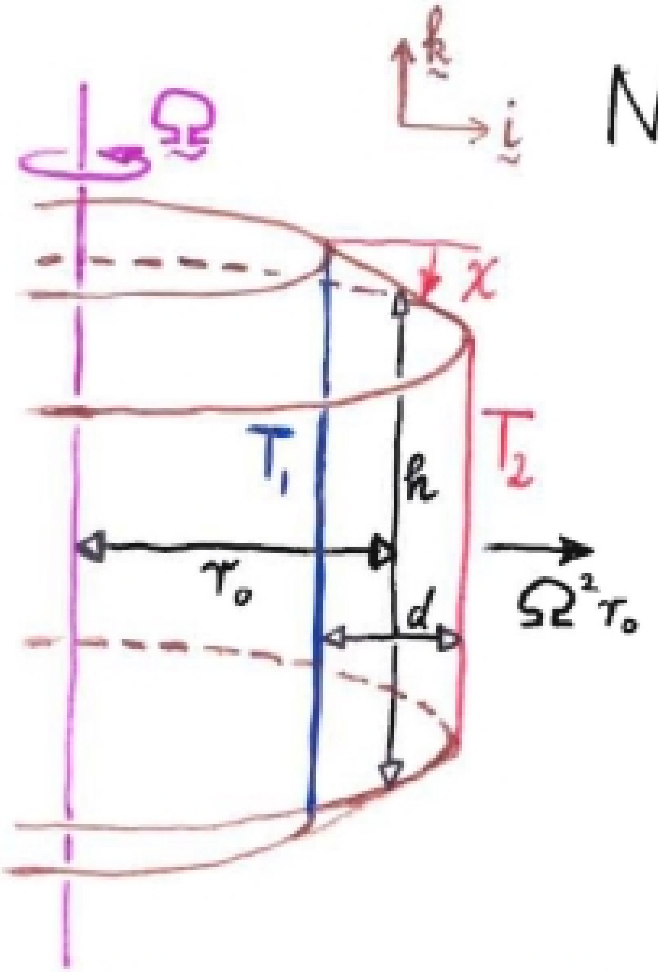
Drive
pulley

Buoyancy Effects in the Rotating Cylindrical Annulus



Nondimensionalisation

length d , time $\frac{d^2}{\nu}$, temperature $(T_2 - T_1)/P$

Basic Equations

$$\nabla \cdot \underset{\sim}{u} = 0$$

$$\frac{\partial}{\partial t}\underset{\sim}{u} + \underset{\sim}{u}\cdot\nabla\underset{\sim}{u} + 2\Omega\,\underset{\sim}{k}\times\underset{\sim}{u} = -\nabla\pi - \underset{\sim}{i}\,R\Theta + \nabla^2\underset{\sim}{u}$$

$$P\left(\frac{\partial}{\partial t} + \underset{\sim}{u}\cdot\nabla\right)\Theta = -\underset{\sim}{i}\cdot\underset{\sim}{u} + \nabla^2\Theta$$

Dimensionless Parameters : $\Omega = \frac{\Omega_D d^2}{\nu}$, $R = \frac{\gamma (T_2 - T_1)\Omega_D^2 r_0 d^3}{\nu \varkappa}$, $P = \frac{\nu}{\varkappa}$

Inviscid linear analysis:

$\underset{\sim}{u} = \nabla\psi(x,y) \times \underset{\sim}{k}\, e^{i\omega t}$, $\Theta = \hat{\Theta} e^{i\omega t}$

$$\left(-i\omega\Delta_2 + \eta^* \frac{\partial}{\partial y}\right)\psi - R\frac{\partial}{\partial y}\hat{\Theta} = 0 \qquad \eta^* = 4\eta_0 \Omega d/k$$

$$iP\omega\hat{\Theta} + \frac{\partial}{\partial y}\psi = 0$$

$$\psi = \cos\pi x\, e^{i\alpha y}$$

$$\hat{\Theta} = -\frac{\alpha}{\omega P}\psi$$

$$P i\omega\left(i\omega(\pi^2+\alpha^2) + i\alpha\eta^*\right) - R\alpha^2 = 0$$

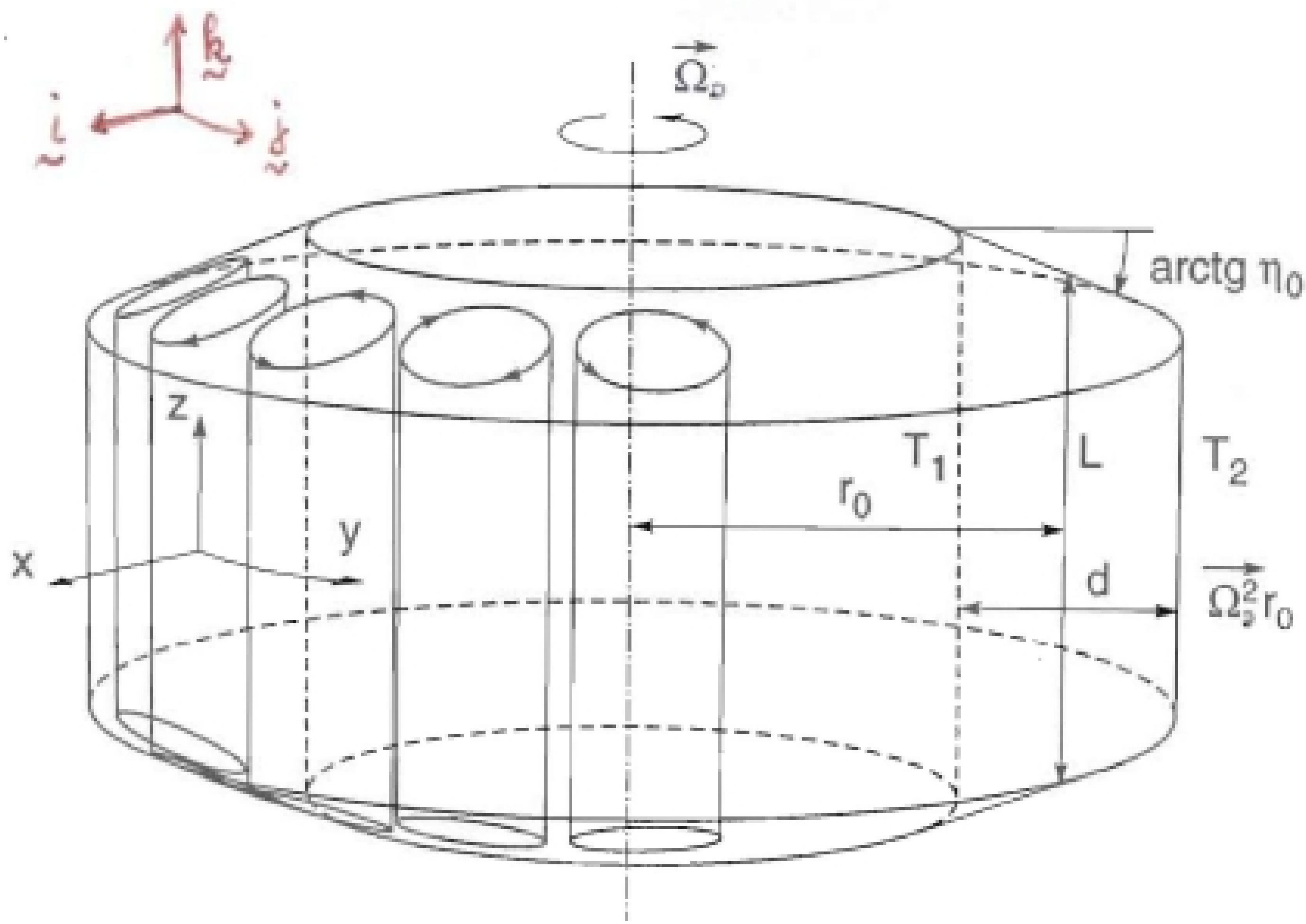
$$\omega = -\frac{\alpha\eta^*}{2(\pi^2+\alpha^2)} \pm \sqrt{\frac{(\alpha\eta^*)^2}{4(\pi^2+\alpha^2)^2} - \frac{R\alpha^2}{P(\pi^2+\alpha^2)}}$$

$$\left.\begin{aligned} \omega_1 &= \frac{-\alpha\eta^*}{\pi^2+\alpha^2} \\ \omega_2 &= -\frac{R\alpha}{\eta^* P} \end{aligned}\right\} \text{ for } R \ll \eta^{*2} P$$

Instability for

$$R > \frac{\eta^{*2} P}{4(\pi^2+\alpha^2)}$$

Convection in a Rotating Cylindrical Annulus



Scales:

length d

time d^2/ν

temperature $(T_2 - T_1)/P$

$\rho = \rho_0(1 - \gamma(T - T_0))$

Basic Equations: $\nabla \cdot \underset{\sim}{u} = 0$

$$\frac{\partial}{\partial t}\underset{\sim}{u} + \underset{\sim}{u}\cdot\nabla\underset{\sim}{u} + 2\Omega\,\underset{\sim}{k}\times\underset{\sim}{u} = -\nabla\pi - \underset{\sim}{i}R\vartheta + \nabla^2\underset{\sim}{u} \qquad \circledast$$

$$P\left(\frac{\partial}{\partial t} + \underset{\sim}{u}\cdot\nabla\right)\vartheta = -\underset{\sim}{i}\cdot\underset{\sim}{u} + \nabla^2\vartheta$$

Dimensionless Parameters: $\Omega \equiv \frac{\Omega_D d^2}{\nu}$, $R \equiv \frac{\gamma(T_2 - T_1)\Omega_D^2 r_0 d^3}{\nu\kappa}$, $P \equiv \frac{\nu}{\kappa}$

Boundary Conditions: $u_z \pm \eta_0 u_x = \frac{\partial}{\partial z}\vartheta = 0$ at $z = \pm\frac{L}{2d}$, $u_x = \vartheta = 0$ at $x = \pm\frac{1}{2}$

Quasi-geostrophic Balance: $2\Omega\,\underset{\sim}{k}\times\underset{\sim}{u} \approx -\nabla\pi \Rightarrow \underset{\sim}{u} = \nabla\psi(x,y,t)\times\underset{\sim}{k} + \dots$

Operation $-\overline{\underset{\sim}{k}\cdot\nabla\times\circledast}^{z}$ yields:

$$\frac{\partial}{\partial t}\Delta_2\psi + \overline{\underset{\sim}{u}}^{z}\cdot\nabla\Delta_2\psi + \frac{2\Omega d}{L}u_z\Big|_{z=-\frac{L}{2d}}^{z=\frac{L}{2d}} = R\frac{\partial}{\partial y}\overline{\vartheta}^{z} + \Delta_2^2\psi$$

where $\Delta_2 \equiv \partial^2/\partial x^2 + \partial^2/\partial y^2$

Two-dimensional Problem:

$$\left[\frac{\partial}{\partial t} + \frac{\partial}{\partial y}\psi\frac{\partial}{\partial x} - \frac{\partial}{\partial x}\psi\frac{\partial}{\partial y}\right]\Delta_2\psi - \eta^*\frac{\partial}{\partial y}\psi - \Delta_2^2\psi = -R\frac{\partial}{\partial y}\vartheta$$

$$P\left[\frac{\partial}{\partial t} + \frac{\partial}{\partial y}\psi\frac{\partial}{\partial x} - \frac{\partial}{\partial x}\psi\frac{\partial}{\partial y}\right]\vartheta + \frac{\partial}{\partial y}\psi - \Delta_2\vartheta = 0$$

with $\eta^* \equiv \frac{4\eta_0\Omega d}{L}$

Linear Analysis

Solution for $\varepsilon = 0$: $\Psi_0 = \sin\pi(x+\frac{1}{2})\exp\{i\alpha y + i\omega t\}$, $\vartheta_0 = \dfrac{-i\alpha\Psi_0}{Pi\omega + \pi^2 + \alpha^2}$

Condition for R_0, ω: $\left[Pi\omega + \alpha^2 + \pi^2\right]\left\{(i\omega + \pi^2 + \alpha^2)(\pi^2 + \alpha^2) + i\alpha\eta^*\right\} - R_0\alpha^2 = 0$

$$\Rightarrow \quad \omega = \frac{-\alpha\eta^*}{(1+P)(\pi^2+\alpha^2)}, \quad R_0 = \frac{(\pi^2+\alpha^2)^3}{\alpha^2} + \left(\frac{\eta^* P}{1+P}\right)^2 (\pi^2+\alpha^2)^{-1}$$

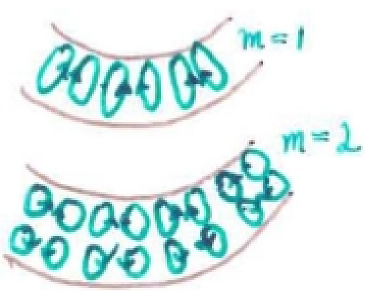
Minimisation of $R_0(\alpha)$ for $\eta^* \to \infty$: $\alpha_c = \left[\dfrac{\eta^* P}{\sqrt{2}(1+P)}\right]^{1/3}$, $R_c = 3\alpha_c^4$

$\Rightarrow$ Onset of convection independent of D for given temperature gradient!

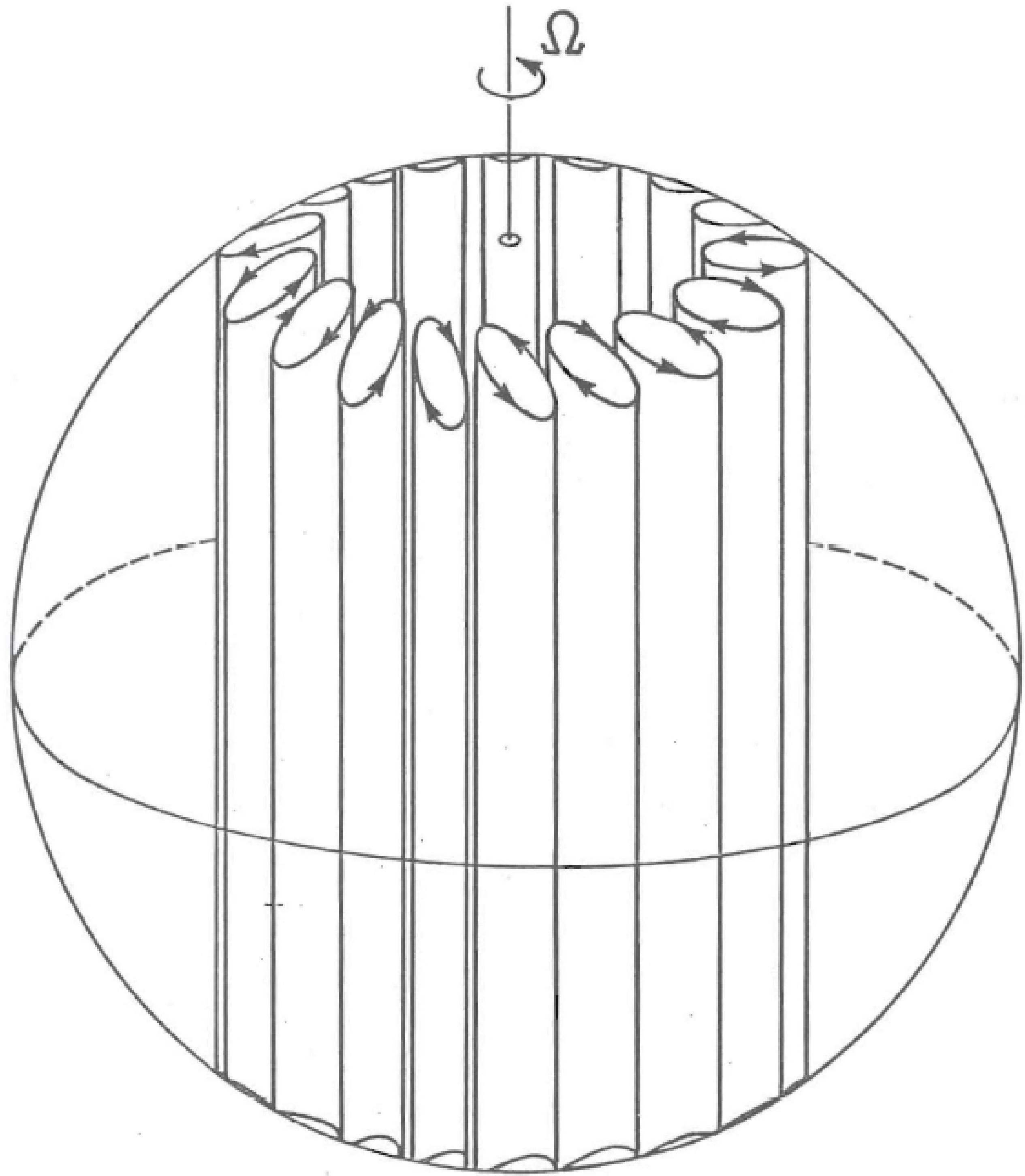
$$\gamma \frac{T_2 - T_1}{D\kappa\nu} g = 3\left(\frac{\alpha_c}{D}\right)^4 = 3\left(\frac{2\pi}{\lambda_c}\right)^4$$

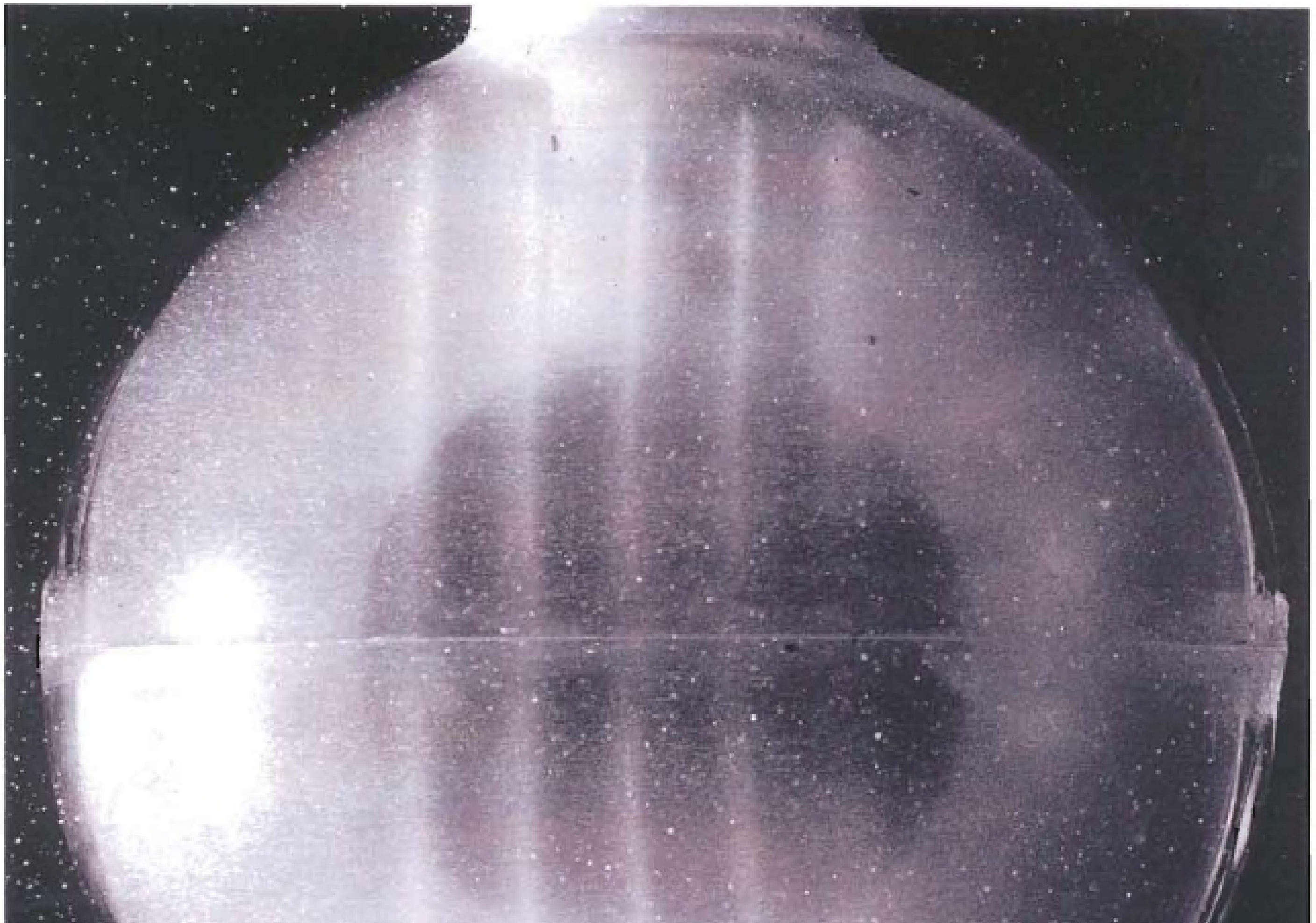
($\Rightarrow$ Application to sphere!)

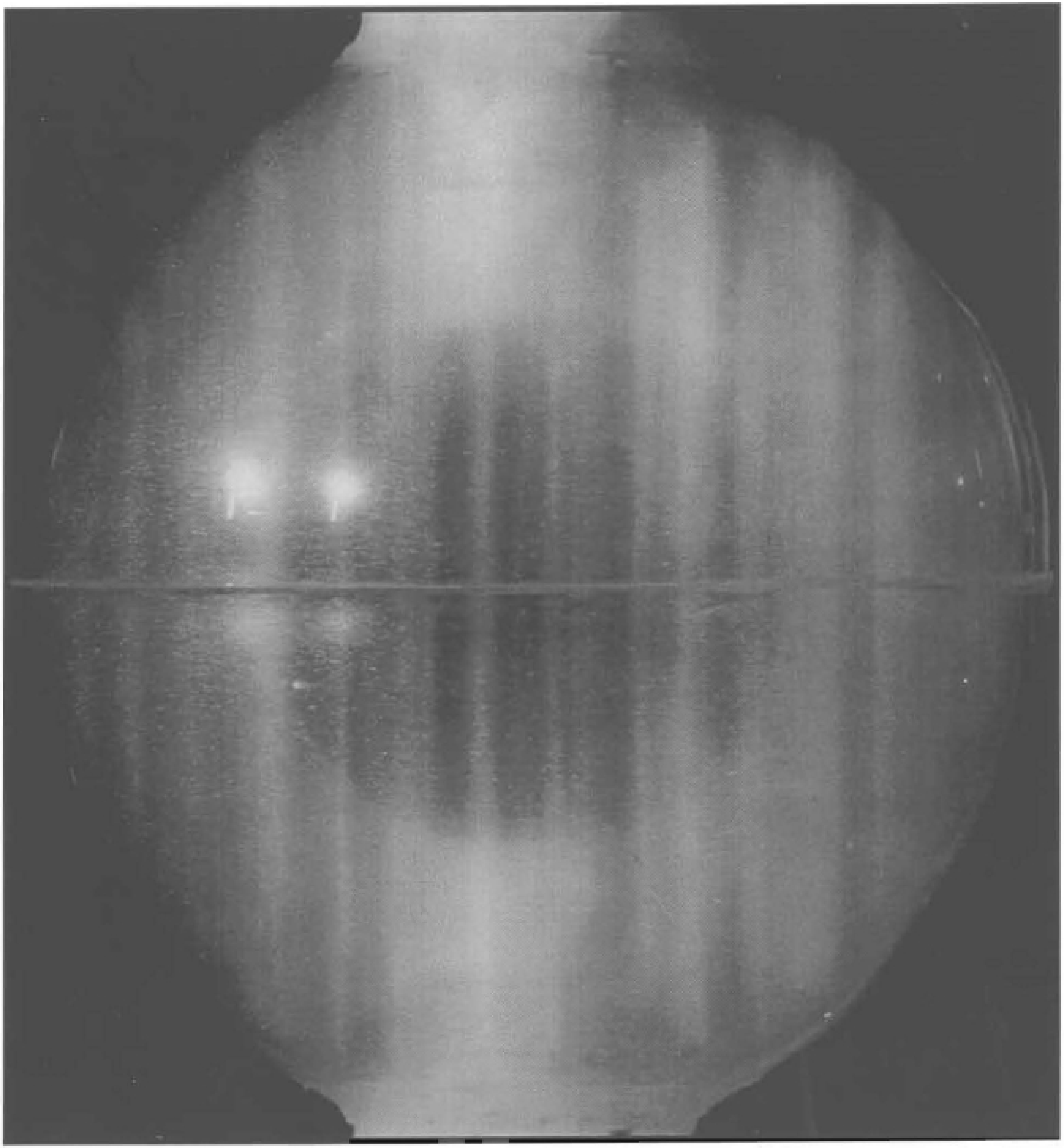
$\Rightarrow$ Modes with $\Psi_0 = \sin m\pi(x+\frac{1}{2})\exp\{i\alpha y + i\omega t\}$ have nearly the same critical Rayleigh number for $\eta^* \to \infty$.

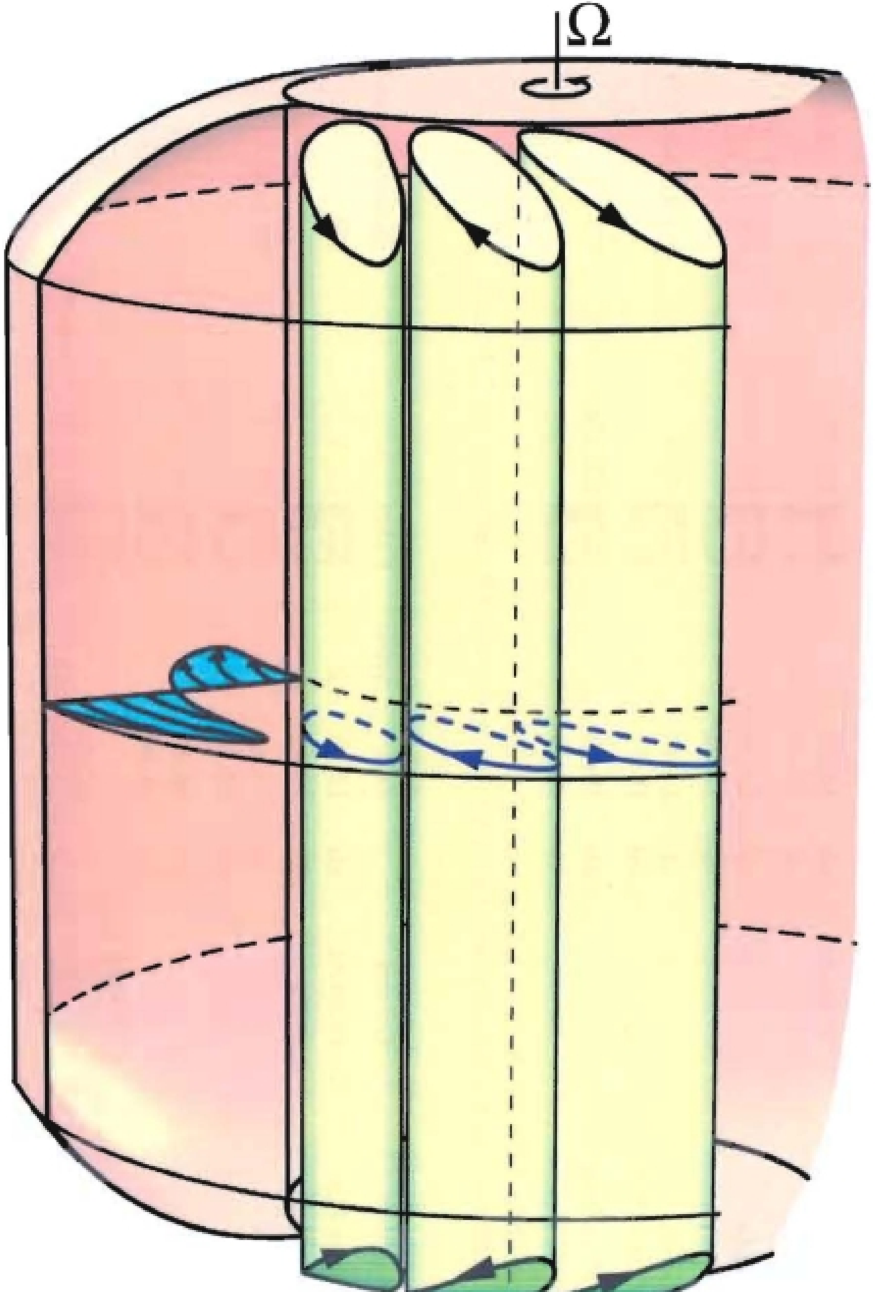


$$R_{mc} = 3\alpha_c^4\left(1 + \frac{m^2\pi^2}{\alpha_c^2} + \dots\right) \quad \text{for } m = 1, 2, 3, \dots$$


Ω



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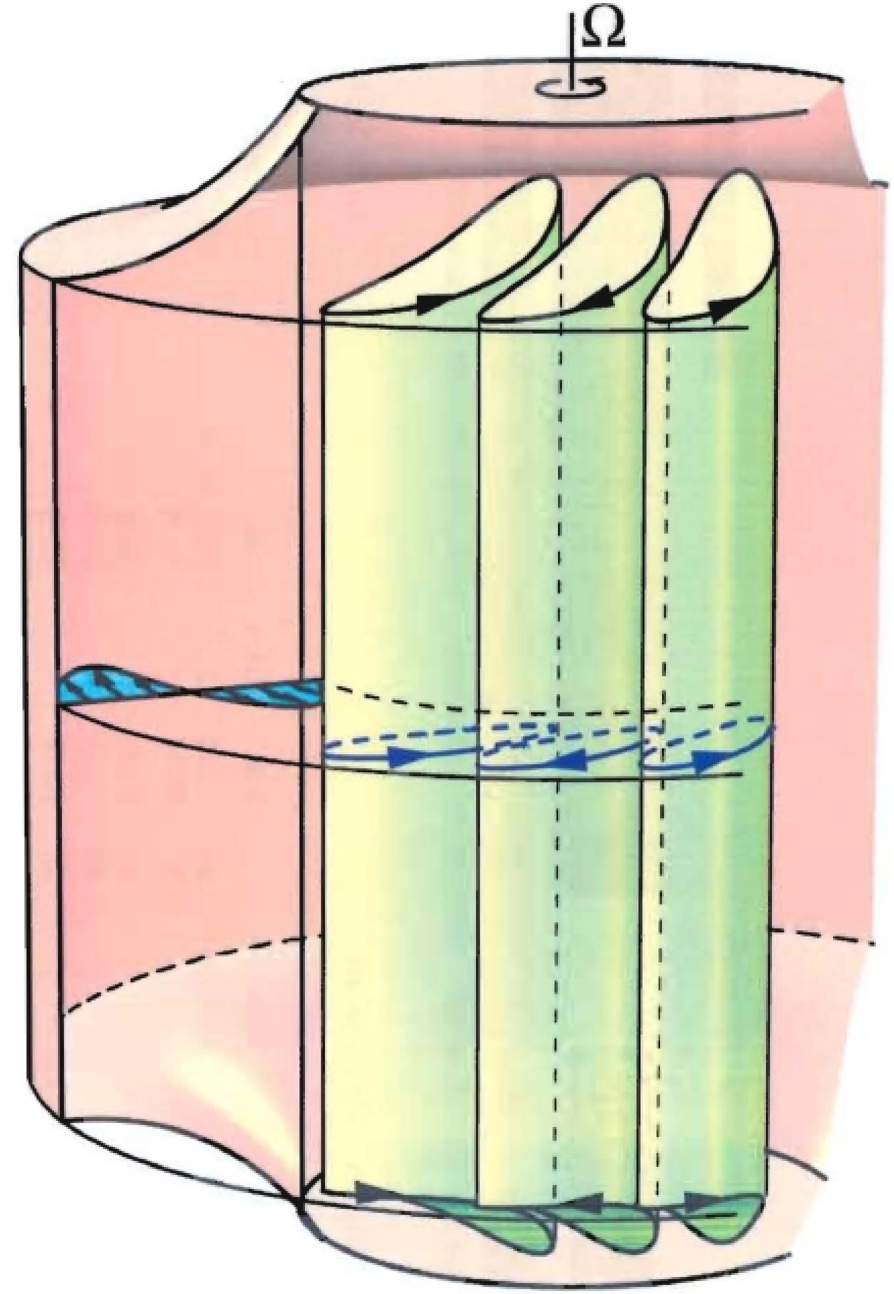
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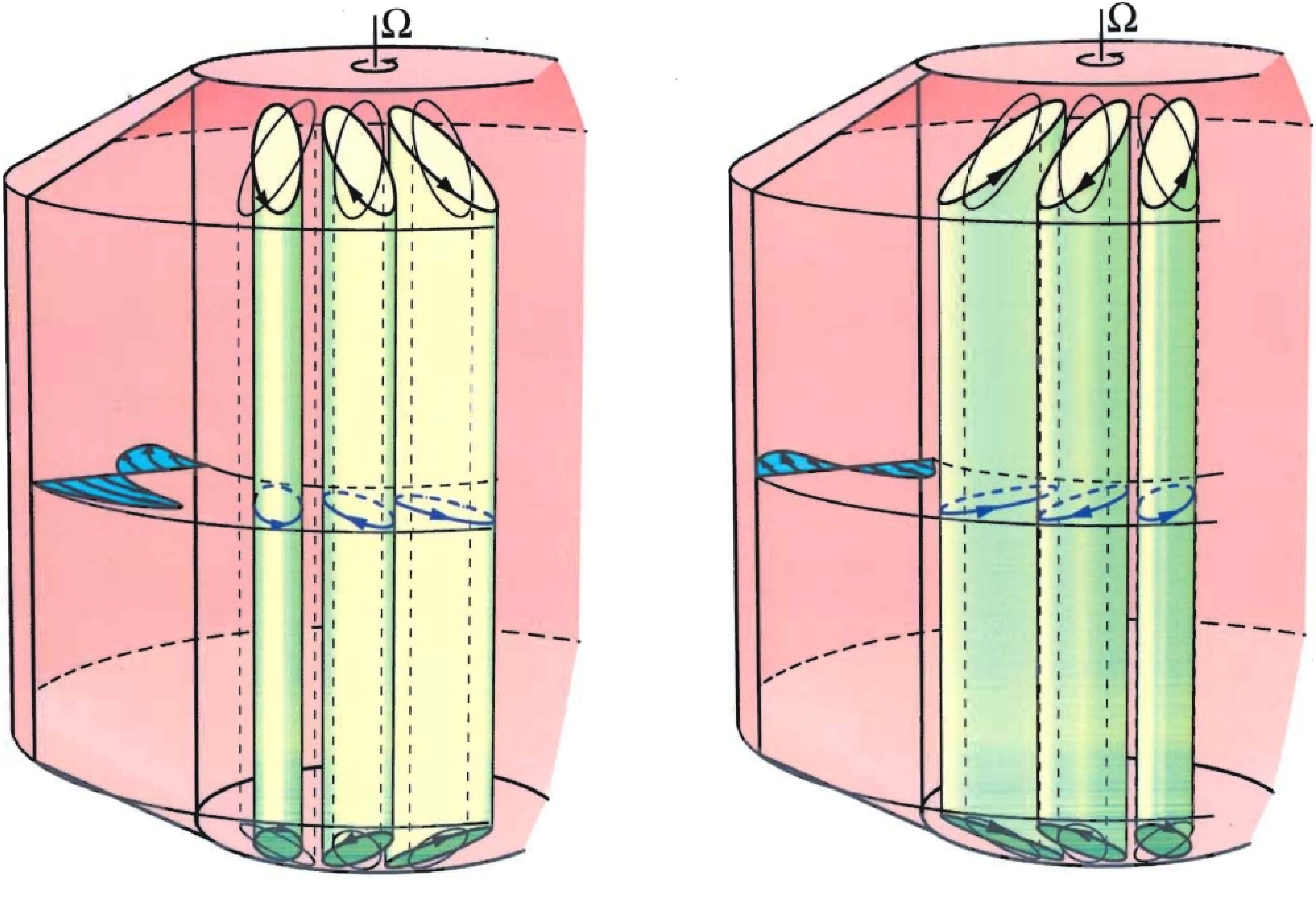
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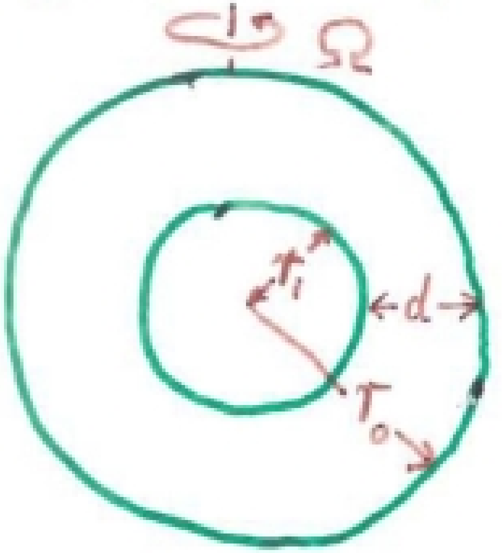
Convection in Rotating Spherical Shells



Basic State: $T_s = T_0 - \frac{1}{2} \hat{r}^2 \beta$

$$\underset{\sim}{g} = -\gamma \hat{\underset{\sim}{r}}$$

$$\varrho = \varrho_0 (1 - \alpha_t (T - T_0))$$

Scaling: $[d]$, $\left[\frac{d^2}{\nu}\right]$, $\left[\frac{\beta d^2 \nu}{\varkappa}\right]$

Basic Equations: $\frac{\partial}{\partial t}\underset{\sim}{u} + \underset{\sim}{u}\cdot\nabla\underset{\sim}{u} + \tau\,\underset{\sim}{k}\times\underset{\sim}{u} = -\nabla\pi + \underset{\sim}{r}R\Theta + \nabla^2\underset{\sim}{u}$

$$\nabla\cdot\underset{\sim}{u} = 0$$

$$\left(\frac{\partial}{\partial t}\Theta + \underset{\sim}{u}\cdot\nabla\Theta\right)P = \underset{\sim}{r}\cdot\underset{\sim}{u} + \nabla^2\Theta$$

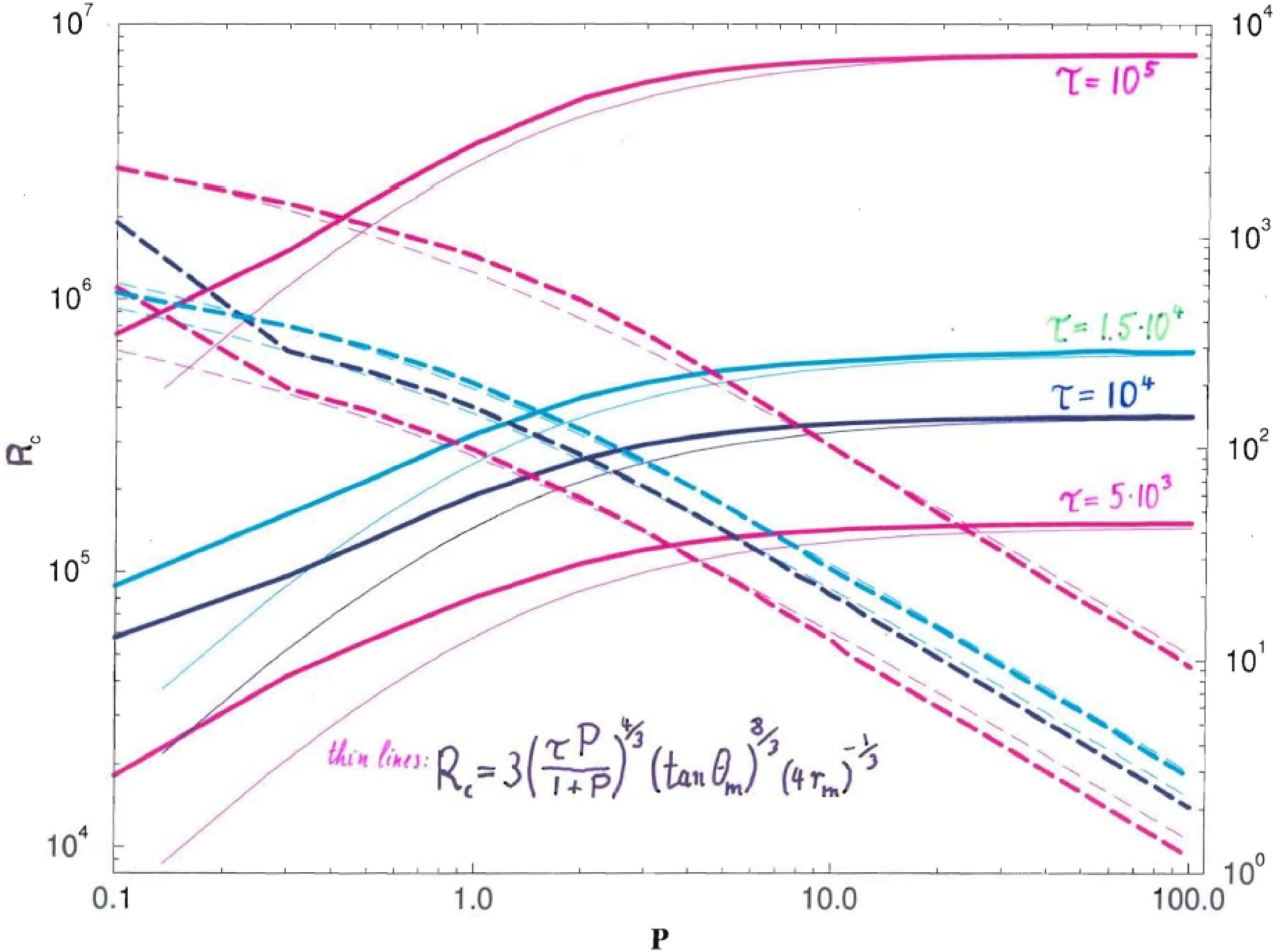
Representation: $\underset{\sim}{u} = \nabla \times (\nabla \times \underset{\sim}{r}\, \Phi) + \nabla \Psi \times \underset{\sim}{r}$

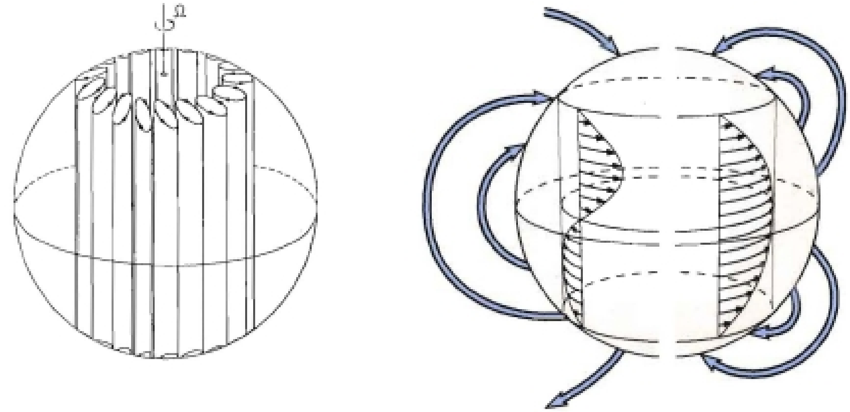
$$
\left.
\begin{aligned}
&\left[\left(\nabla^2 - \frac{\partial}{\partial t}\right) L_2 + \tau \frac{\partial}{\partial \varphi}\right] \nabla^2 \Phi + \tau Q \Psi - R L_2 \Theta = -\underset{\sim}{r} \cdot \nabla \times (\nabla \times (\underset{\sim}{u} \cdot \nabla \underset{\sim}{u})) \\
&\left[\left(\nabla^2 - \frac{\partial}{\partial t}\right) L_2 + \tau \frac{\partial}{\partial \varphi}\right] \Psi - \tau Q \Phi = \underset{\sim}{r} \cdot \nabla \times (\underset{\sim}{u} \cdot \nabla \underset{\sim}{u}) \\
&\left(\nabla^2 - P \frac{\partial}{\partial t}\right) \Theta + L_2 \Phi = P (\underset{\sim}{u} \cdot \nabla \Theta) \\
&L_2 \equiv r \frac{\partial^2}{\partial r^2} r - r^2 \nabla^2, \quad Q \equiv \underset{\sim}{k} \cdot \nabla - \tfrac{1}{2}\left(L_2 \underset{\sim}{k} \cdot \nabla + \underset{\sim}{k} \cdot \nabla L_2\right)
\end{aligned}
\right\} \circledast
$$

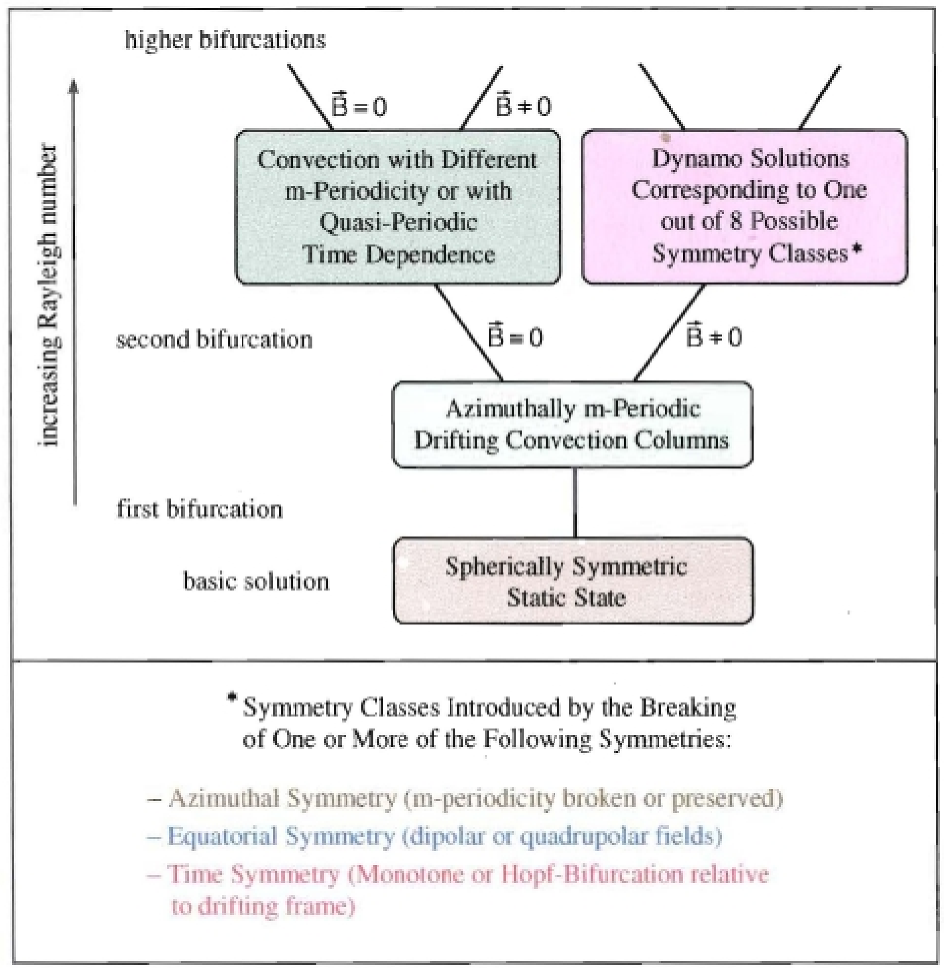
Stress-free, isothermal boundaries: $\Phi = \frac{\partial^2}{\partial r^2} \Phi = \frac{\partial}{\partial r} \frac{\Psi}{r} = \Theta = 0$ at $r = r_{i,o}$

Dimensionless parameters: $R = \frac{\alpha_T \gamma \beta d^6}{\nu \kappa}$, $\tau = \frac{2 \Omega d^2}{\nu}$, $P = \frac{\nu}{\kappa}$

Rayleigh number R_c and frequency ω_c for onset of convection in rotating spherical fluid shells with $\eta = 0.4$



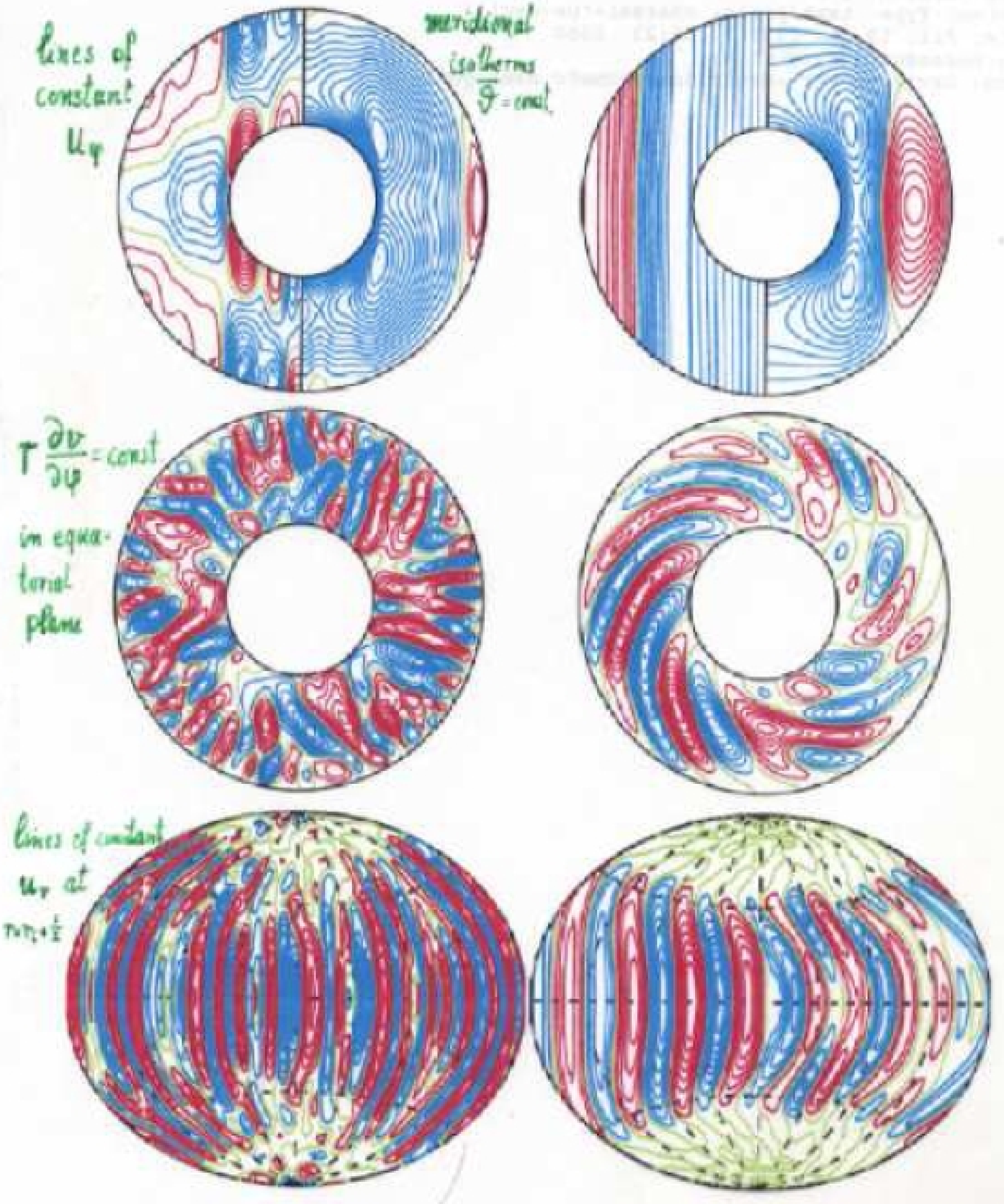


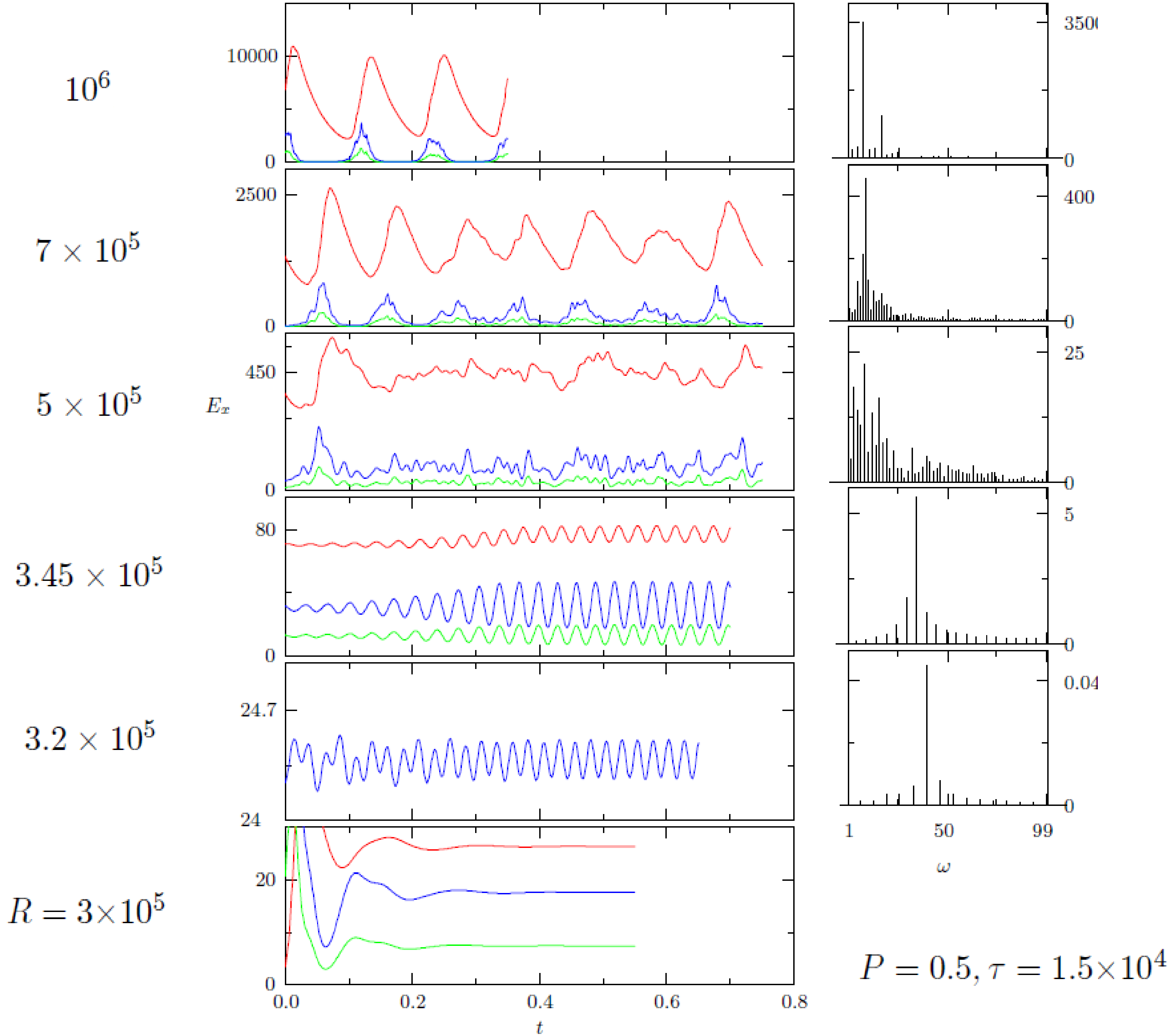


higher bifurcations
$\vec{B} = 0$
$\vec{B} \neq 0$
Convection with Different m-Periodicity or with Quasi-Periodic Time Dependence
Dynamo Solutions Corresponding to One out of 8 Possible Symmetry Classes*
increasing Rayleigh number
second bifurcation
$\vec{B} = 0$
$\vec{B} \neq 0$
Azimuthally m-Periodic Drifting Convection Columns
first bifurcation
basic solution
Spherically Symmetric Static State
* Symmetry Classes Introduced by the Breaking of One or More of the Following Symmetries:
– Azimuthal Symmetry (m-periodicity broken or preserved)
– Equatorial Symmetry (dipolar or quadrupolar fields)
– Time Symmetry (Monotone or Hopf-Bifurcation relative to drifting frame)

Thermal Convection in Spherical Fluid Shells

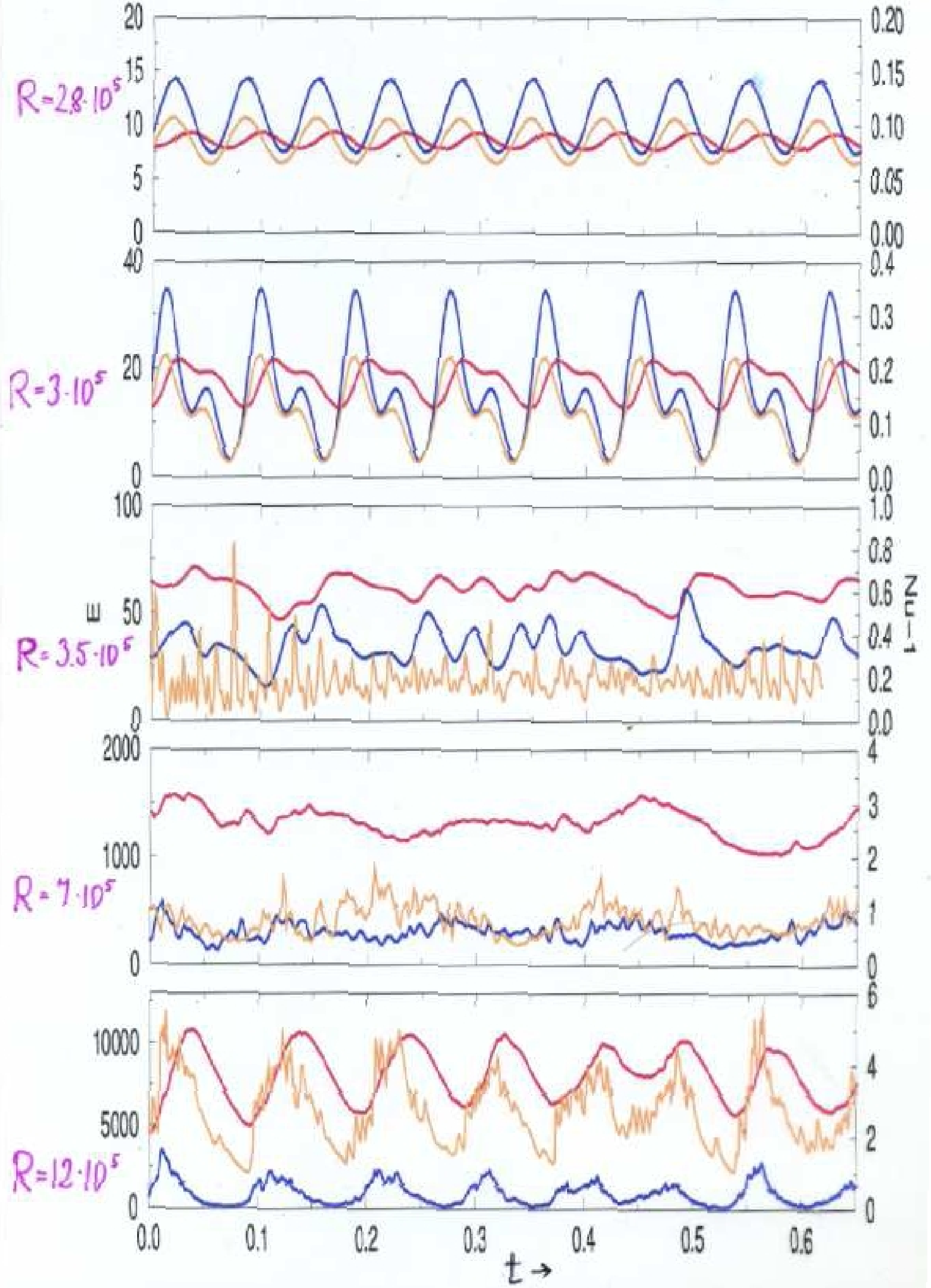
$P = 15,\ \tau = 5 \cdot 10^3,\ R = 8 \cdot 10^5$ $\quad$ $P = 1,\ \tau = 10^4,\ R = 4 \cdot 10^5$

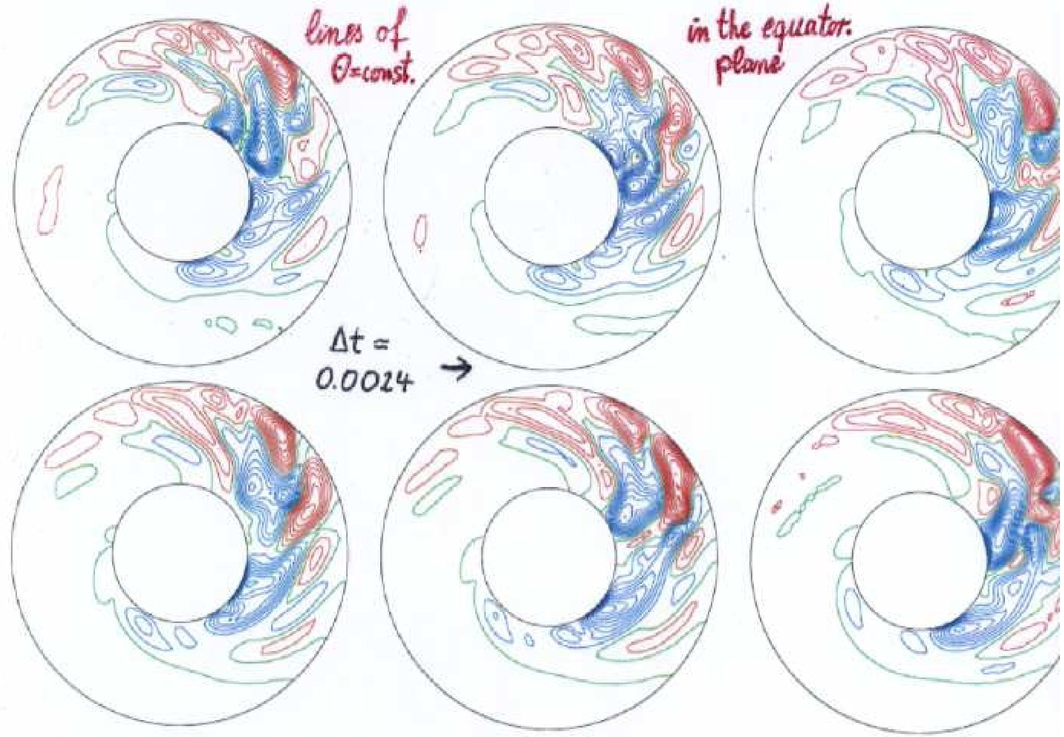




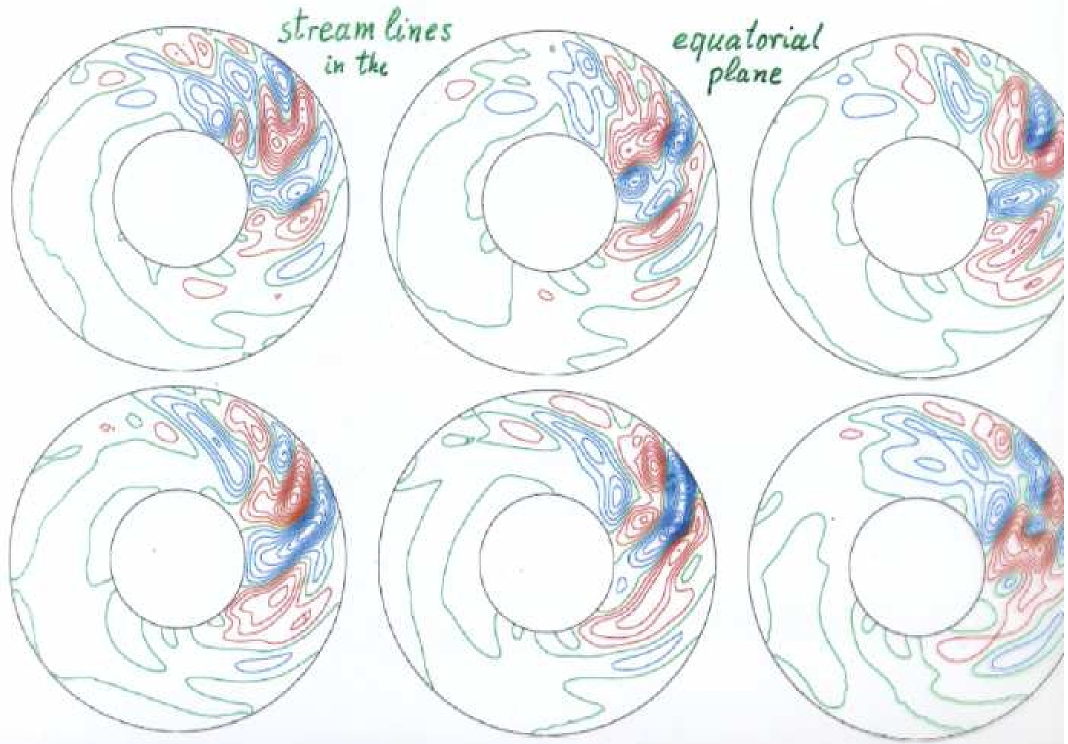
10^6
7×10^5
5×10^5
3.45×10^5
3.2×10^5
$R = 3\times10^5$
E_x
10000
2500
450
80
24.7
24
20
0
0.0
0.2
0.4
0.6
0.8
t
3500
400
25
5
0.04
1
50
99
ω
$P = 0.5, \tau = 1.5\times10^4$

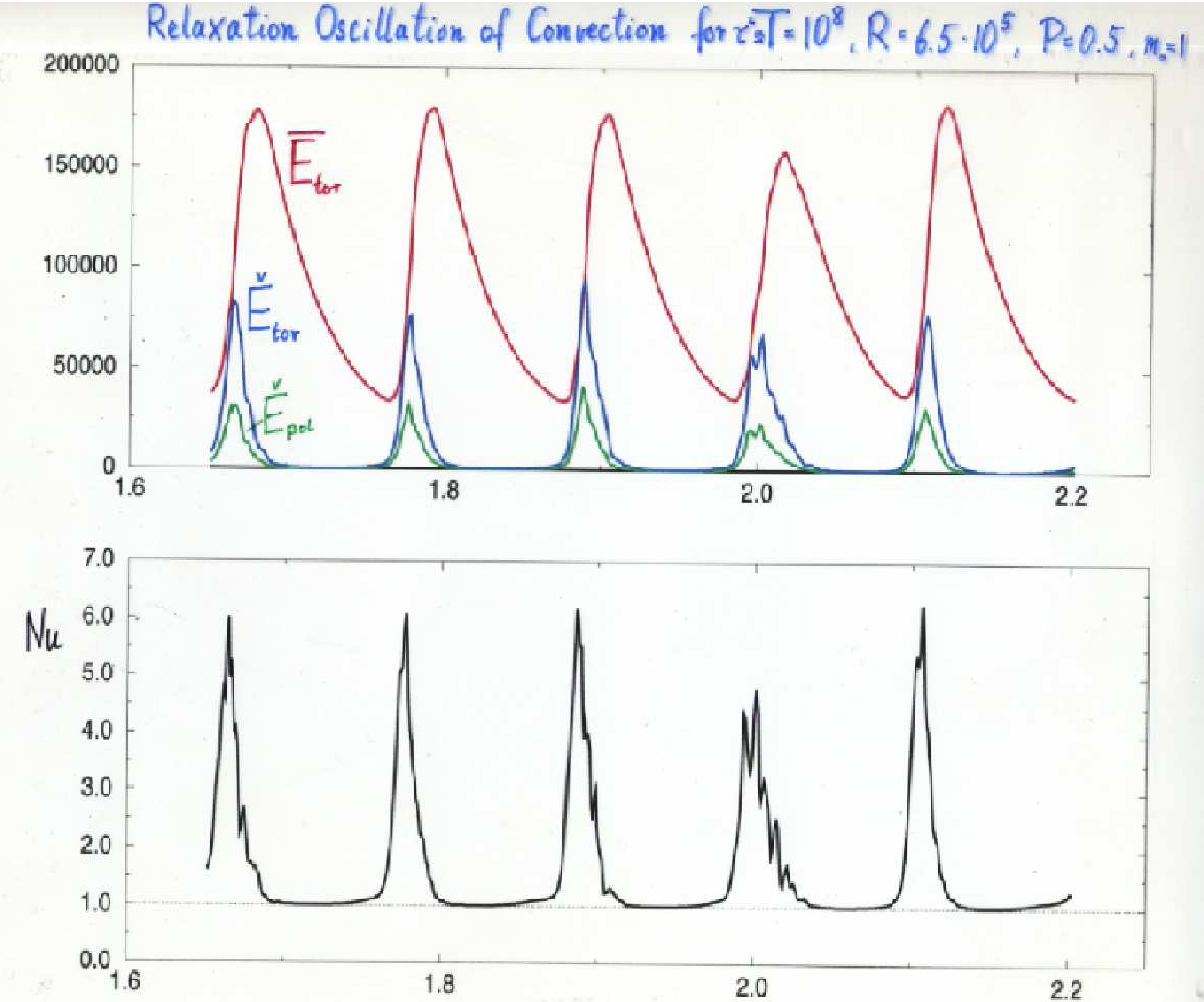
Time Series for Convection with $\tau = 10^4$, $P = 1$, $\eta = 0.4$



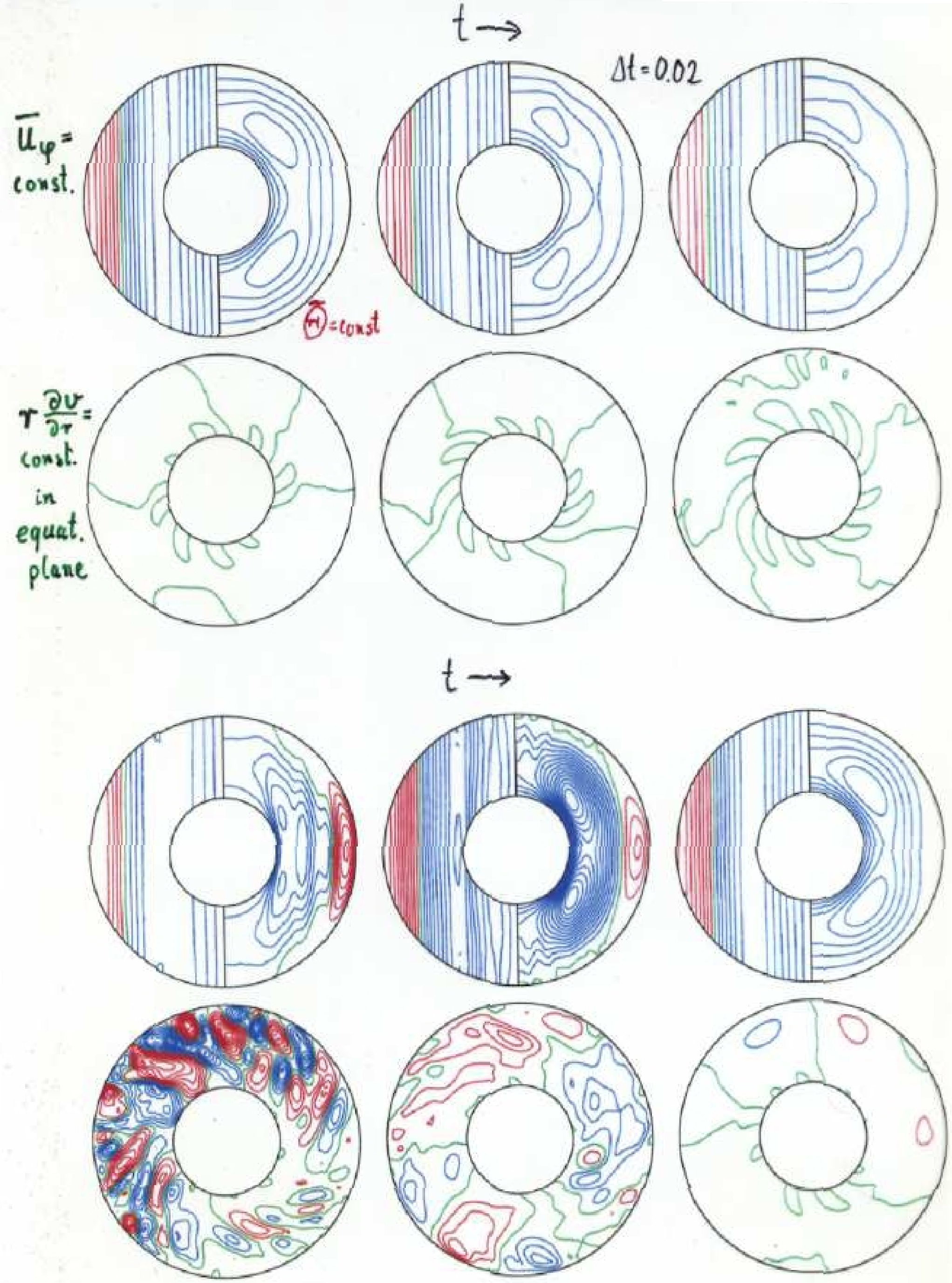


Localized convection for $\tau = 10^4$, $R = 7.5 \cdot 10^5$, $P = 1$





Relaxation Oscillation of Convection for $\tau^2 T = 10^8$, $R = 6.5 \cdot 10^5$, $P = 0.5$, $m_s = 1$
200000
150000
100000
50000
0
1.6
1.8
2.0
2.2
$\overline{E}_{tor}$
$\check{E}_{tor}$
$\check{E}_{pol}$
Nu
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
1.6
1.8
2.0
2.2

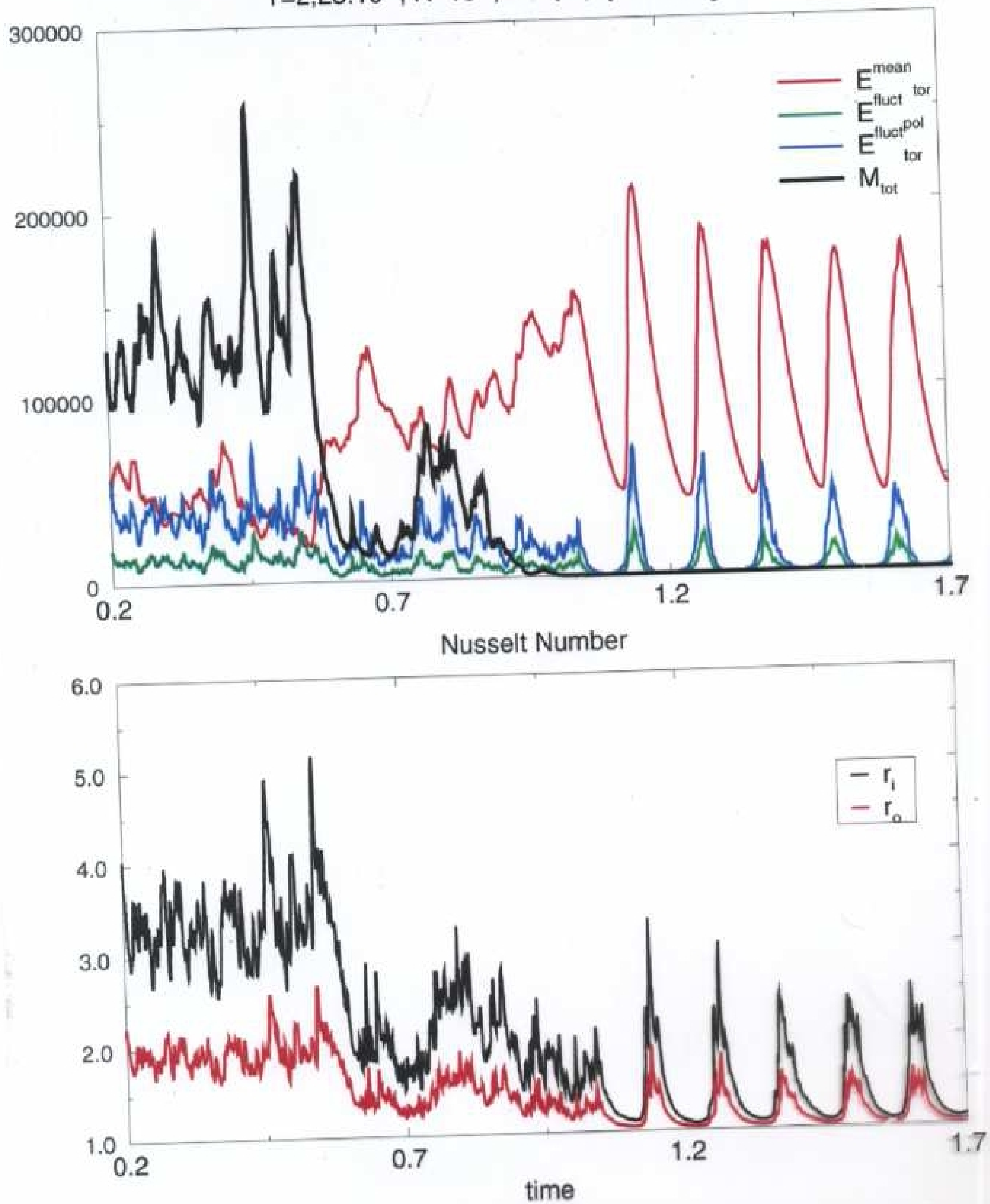


Relaxation Oscillation of Convection

$T = 2.25 \cdot 10^8$, $R = 1.2 \cdot 10^6$, $P = 0.5$

Resumption of Relaxation Oscillation after Decay of Magnetic Field

$T=2,25.10^{8}$; $R=10^{6}$; $P=0,5$; $\eta=0.4$; $m_0=1$



Generation of Magnetic Fields by Convection in Rotating Spherical Fluid Shells

Basic Equations: Equation of Motion:

$$\left(\frac{\partial}{\partial t} + \underset{\sim}{u}\cdot\nabla\right)\underset{\sim}{u} + 2\underset{\sim}{\Omega}\times\underset{\sim}{u} = -\nabla\pi - \alpha_t \Theta \underset{\sim}{g} + \nu\nabla^2\underset{\sim}{u} + \frac{1}{\rho\mu}(\nabla\times\underset{\sim}{B})\times\underset{\sim}{B}$$

$$\nabla\cdot\underset{\sim}{u} = 0 \Rightarrow \underset{\sim}{u} = \nabla\times(\nabla\times\underset{\sim}{r}v) + \nabla\times\underset{\sim}{r}w$$

Energy equation:

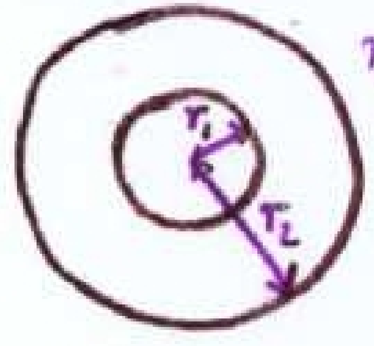
$$\left(\frac{\partial}{\partial t} + \underset{\sim}{u}\cdot\nabla\right)\Theta + \underset{\sim}{u}\cdot\nabla(T_s - T_{is}) = \varkappa\nabla^2\Theta$$

Induction equation:

$$\left(\frac{\partial}{\partial t} + \underset{\sim}{u}\cdot\nabla\right)\underset{\sim}{B} - \lambda\nabla^2\underset{\sim}{B} = \underset{\sim}{B}\cdot\nabla\underset{\sim}{u}$$

$$\nabla\cdot\underset{\sim}{B} = 0 \Rightarrow \underset{\sim}{B} = \nabla\times(\nabla\times\underset{\sim}{r}h) + \nabla\times\underset{\sim}{r}g$$

Basic State: $T_s - T_{is} = T_0 - \frac{1}{2}\beta r^2$



$\eta \equiv \frac{r_1}{r_2}$ $\quad \mathbf{g} = -\hat{\gamma}\,\mathbf{r}/r_2$

Dimensionless Description with

$[r_2 - r_1]$, $\left[\frac{(r_2-r_1)^2}{\nu}\right]$, $[\beta r_2^2]$, $\left[\sqrt{\varrho\mu}\,\frac{r_2-r_1}{\nu}\right]$

Boundary Conditions: $\frac{\partial^2 v}{\partial r^2} = v = \frac{\partial}{\partial r}\frac{w}{r} = \Theta = g = 0$ at $r = r_i,$

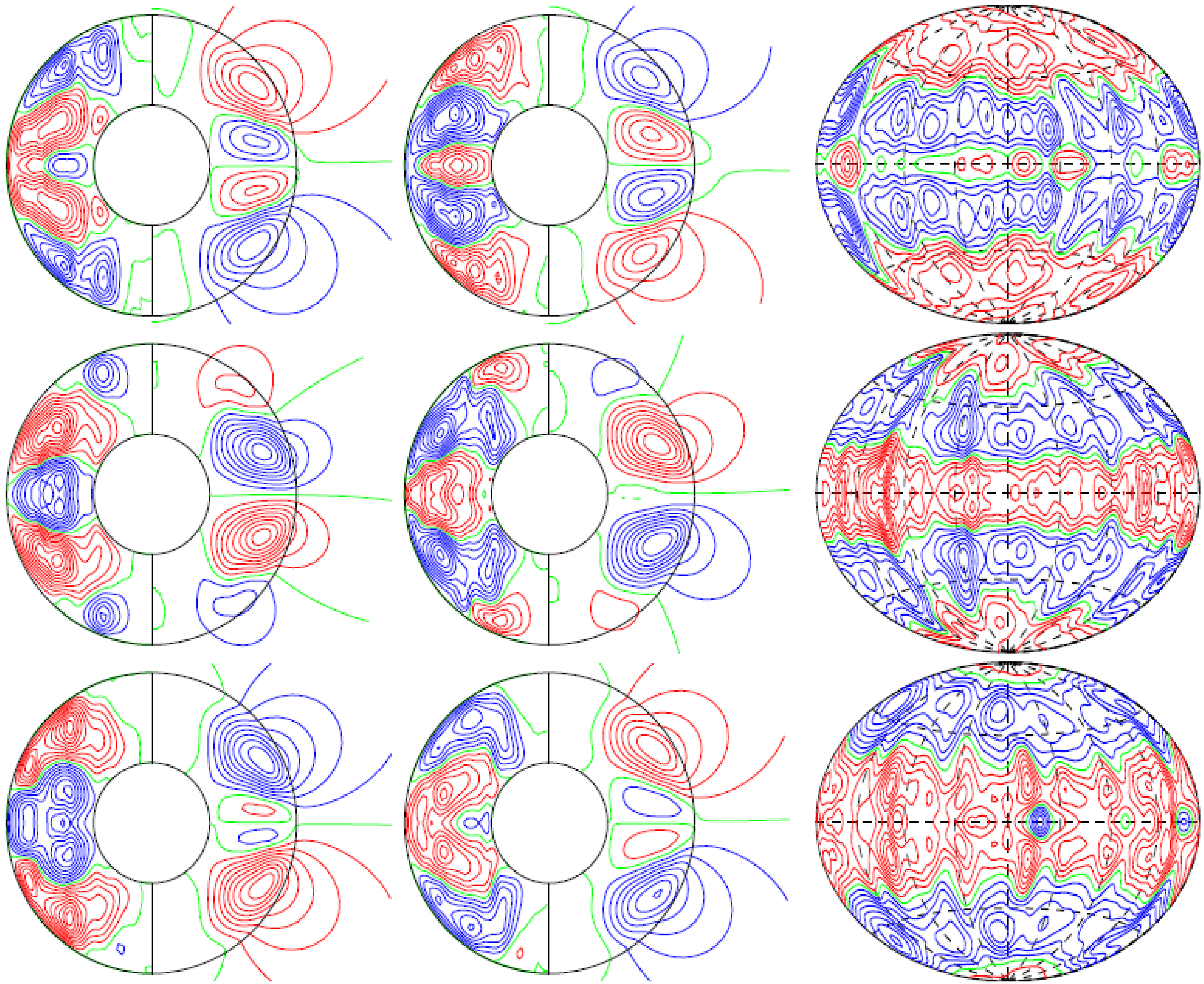
$$h = \sum_\ell h_\ell Y_\ell(\vartheta,\varphi) \; : \quad \frac{\partial}{\partial r} h_\ell = \begin{cases} -(\ell+1)/r_o \cdot h_\ell & \text{at } r = r_o \equiv \frac{1}{1-\eta} \\ \ell/r_i \cdot h_\ell & \text{at } r = r_i \equiv \frac{\eta}{1-\eta} \end{cases}$$

Dimensionless Parameters: $R \equiv \frac{\alpha_t \hat{\gamma} \beta (r_2-r_1)^5}{\nu\kappa}$, $\tau \equiv \frac{2\Omega (r_2-r_1)^2}{\nu} \equiv T$

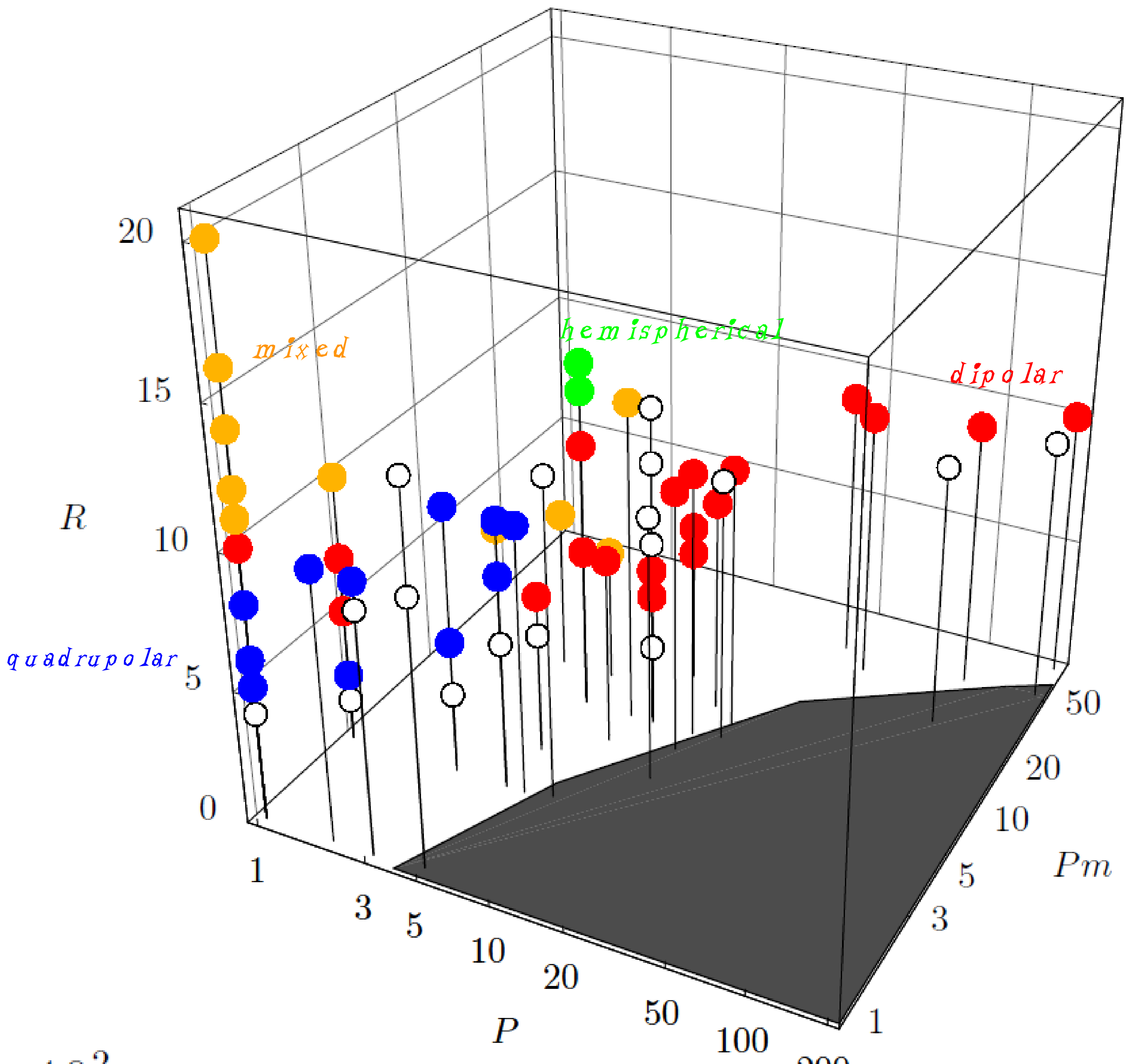
$P \equiv \frac{\nu}{\kappa}$, $\quad P_m \equiv \frac{\nu}{\lambda}$

A period of quadrupolar dynamo oscillations

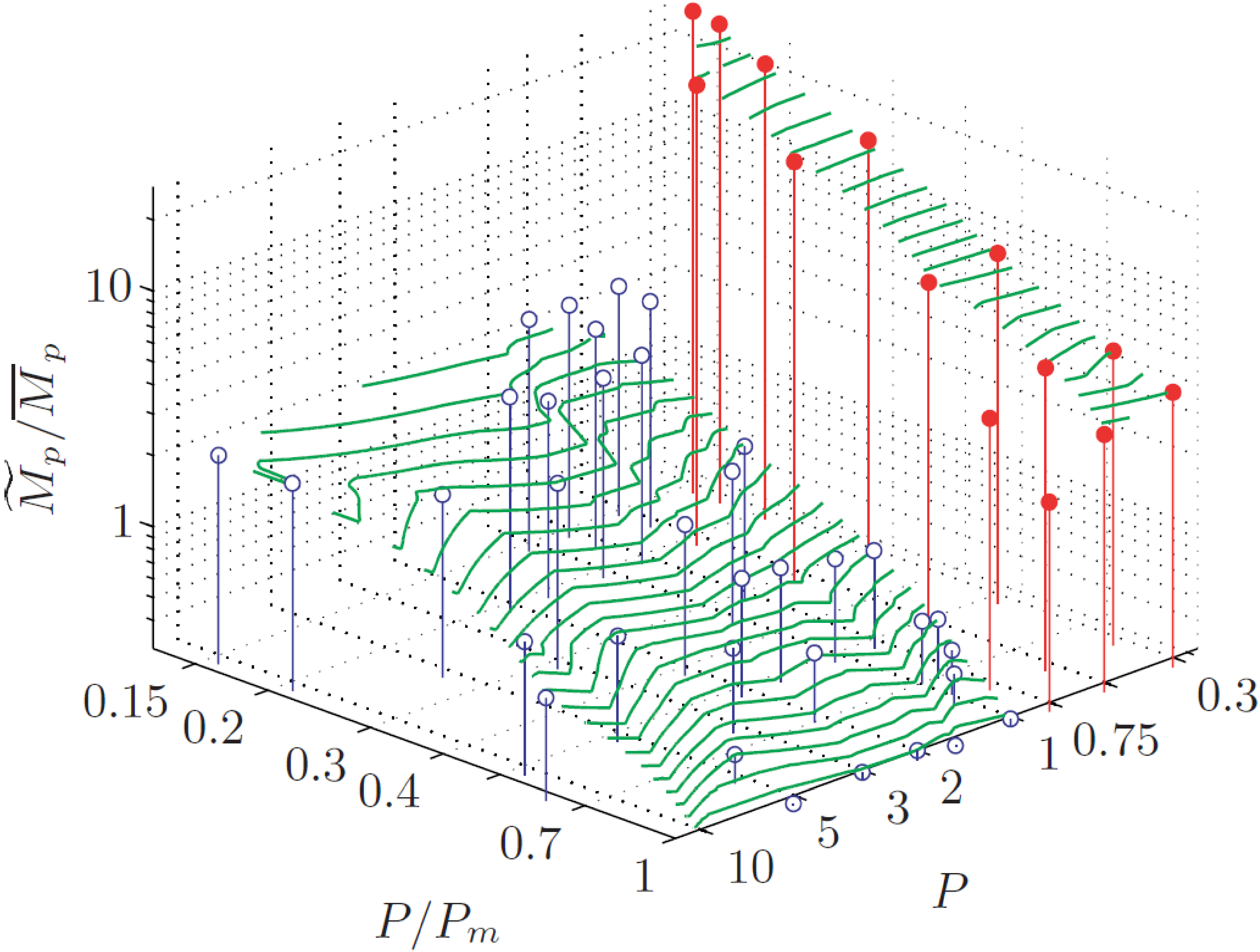
$$P = 5,\ \tau = 5 \times 10^3,\ R = 8 \cdot 10^5,\ P_m = 3.$$



Where do convection-driven dynamos exist?



$\tau = 5 \times 10^3$

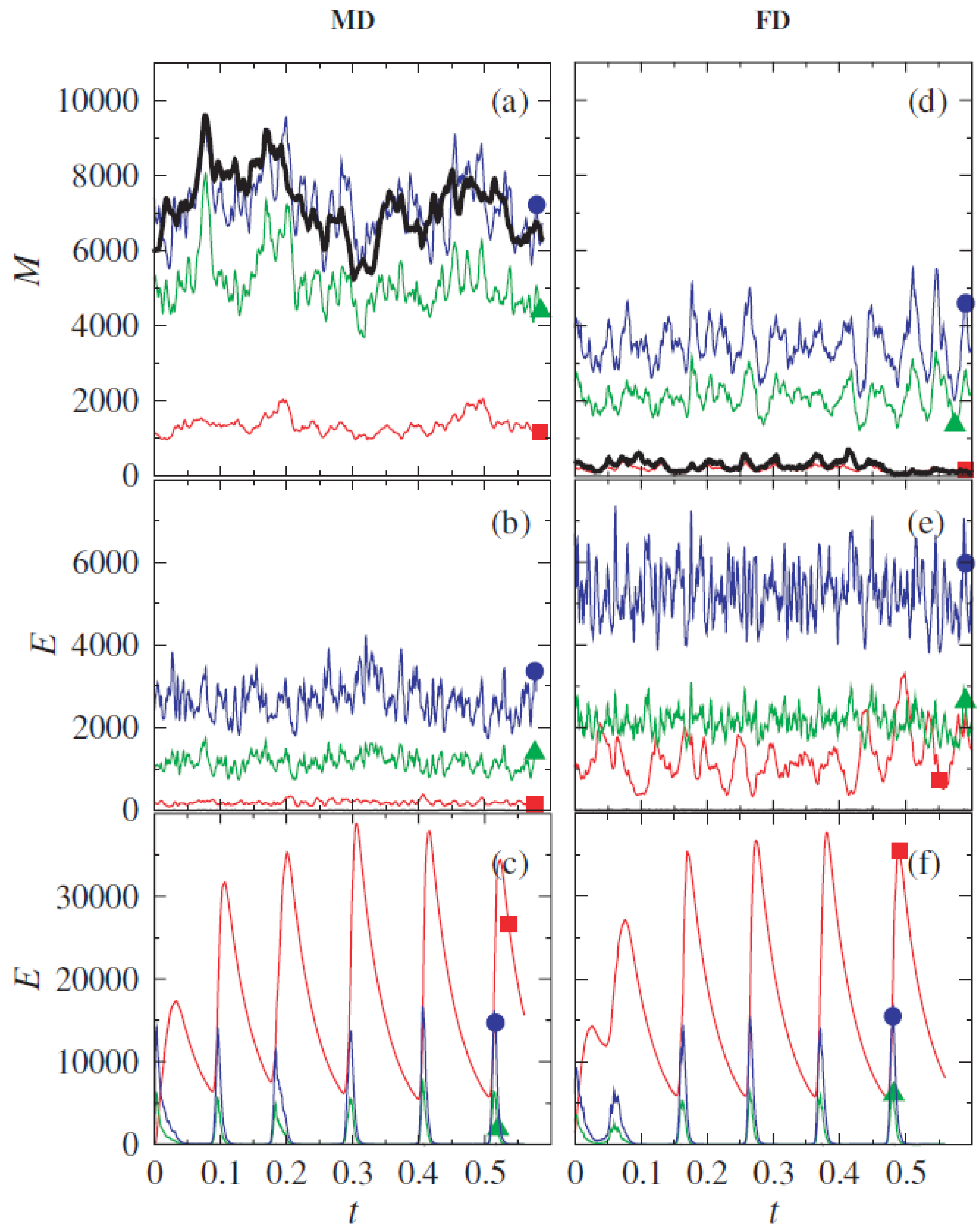


$\widetilde{M}_p/\overline{M}_p$
10
1
0.15
0.2
0.3
0.4
0.7
1
P/P_m
10
5
3
2
1
0.75
0.3
P

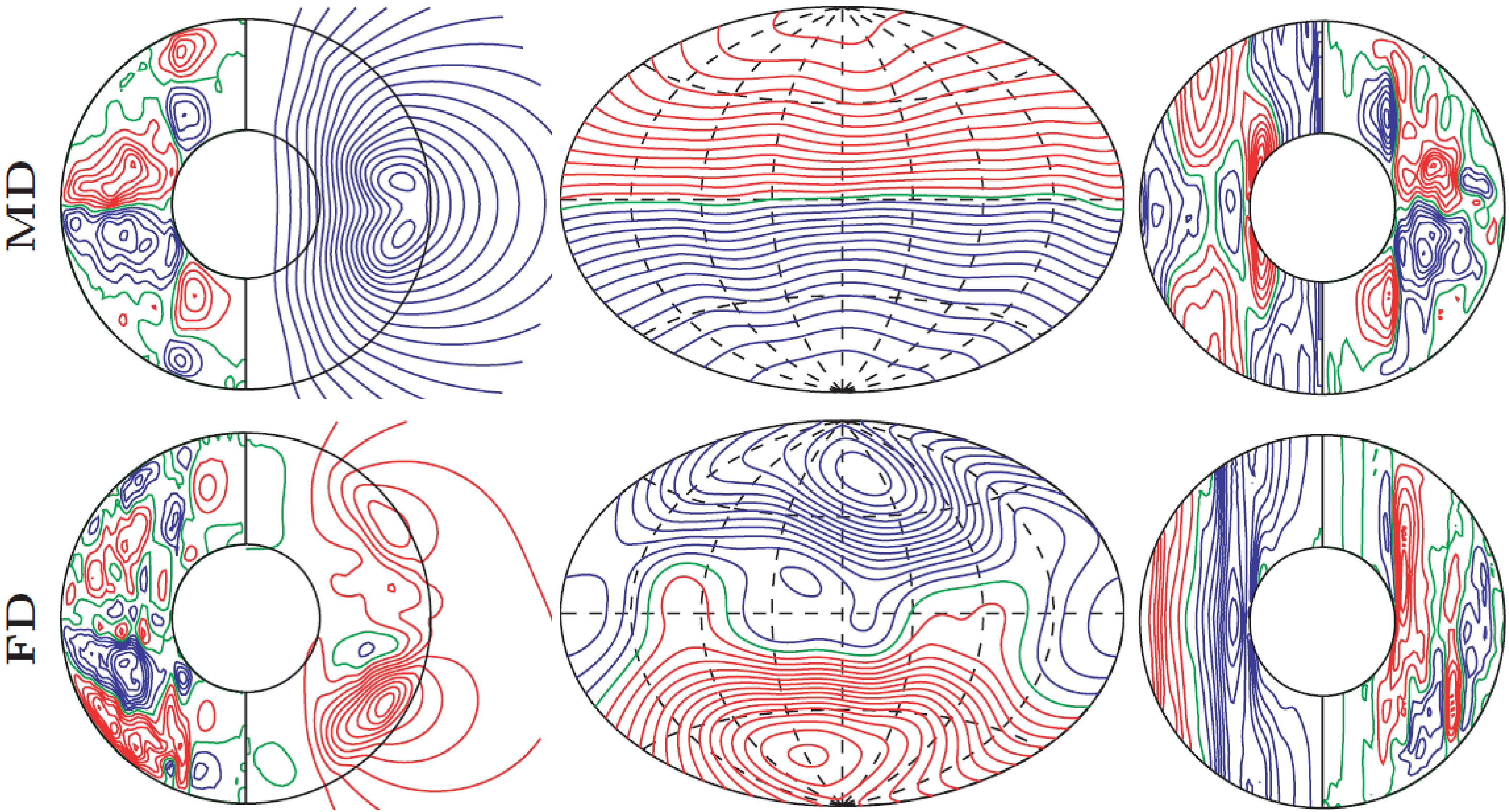
$R = 3.5 \times 10^6$

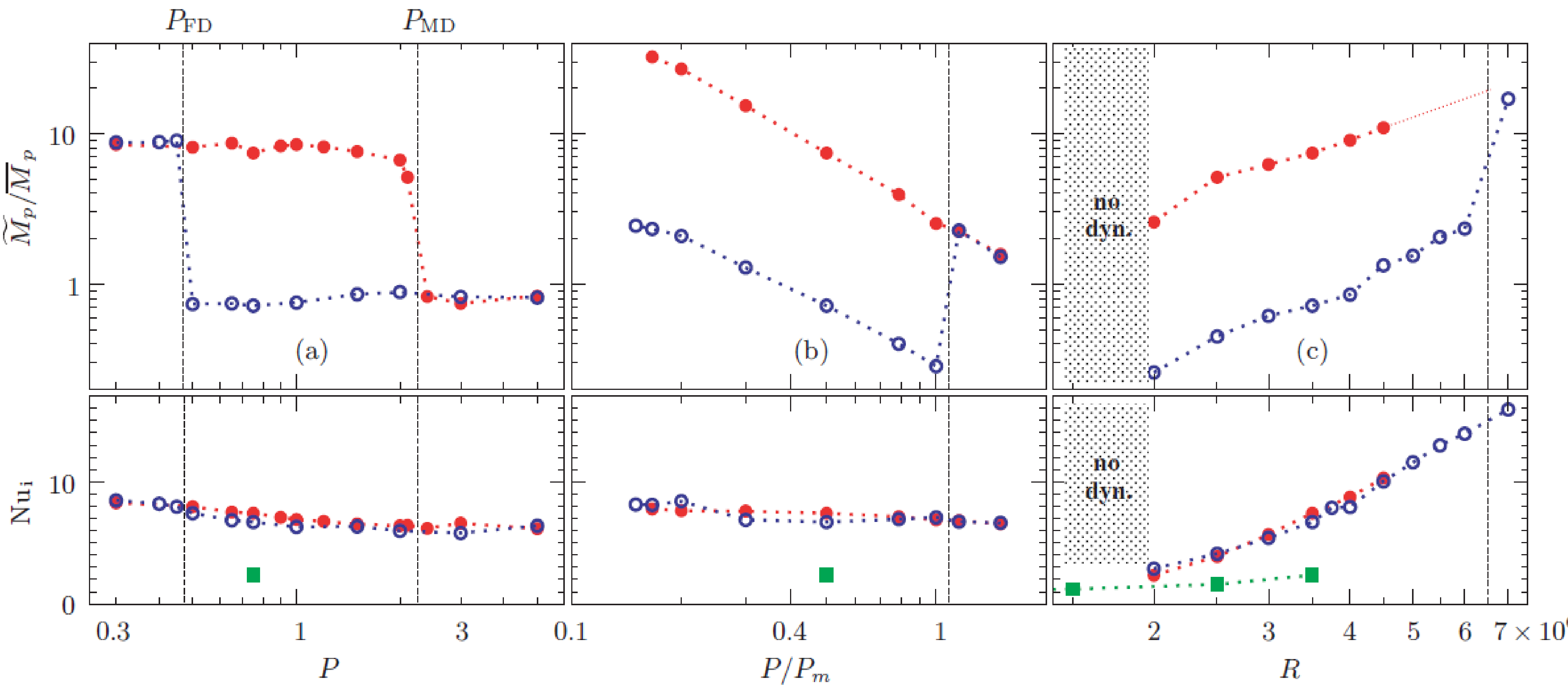
$P_m = 1.5$

$\tau = 3 \times 10^4,\ P = 0.75$



$$R = 3.5 \times 10^6,\ \tau = 3 \times 10^4,\ P = 0.75 \text{ and } P_m = 1.5$$



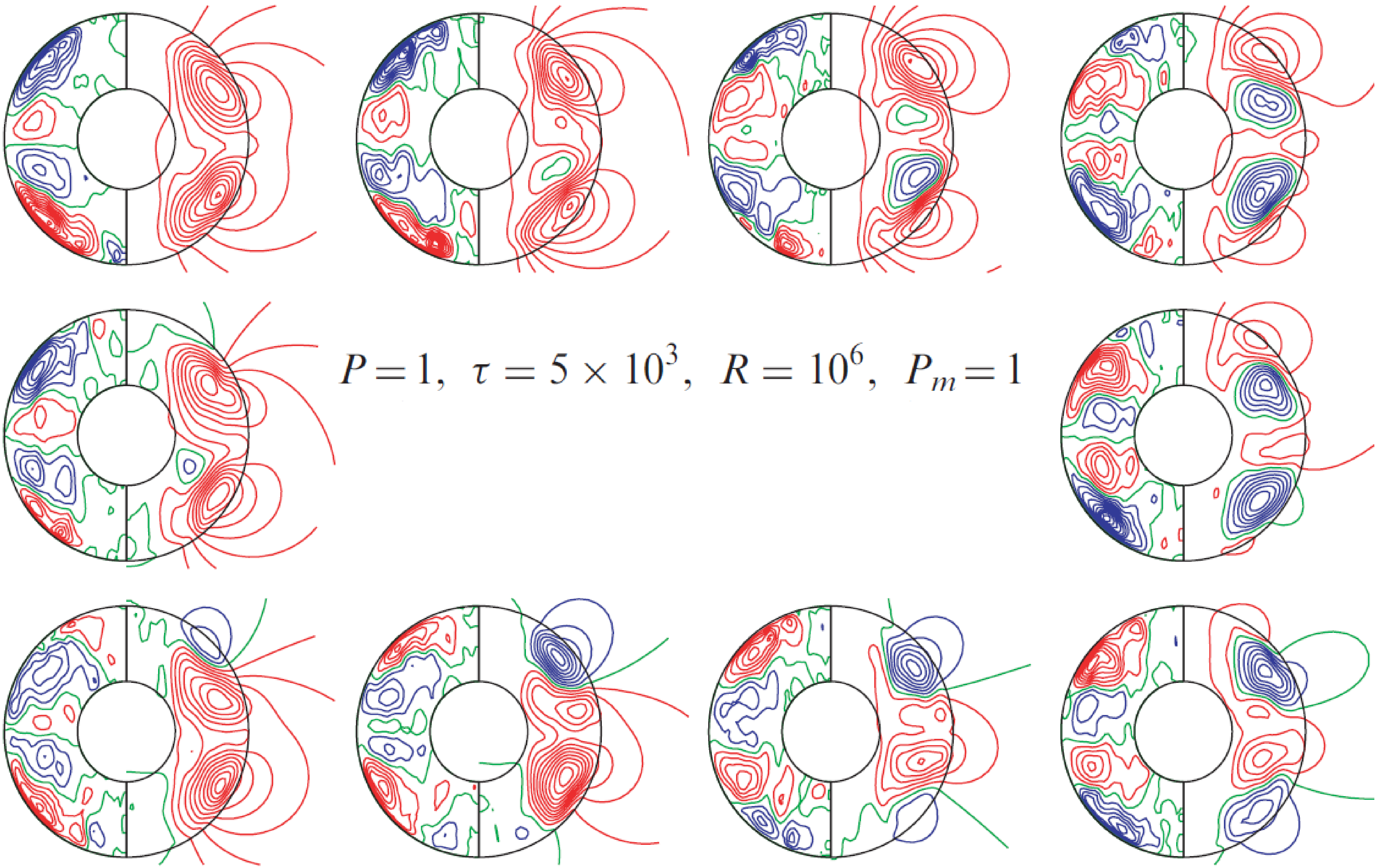


$P/P_m = 0.5$ $\quad$ $P = 0.75$ $\quad$ $P = 0.75,\ P_m = 1.5.$

$R = 3.5\times10^6$

$\tau = 3\times10^4$

A period of dipolar oscillations



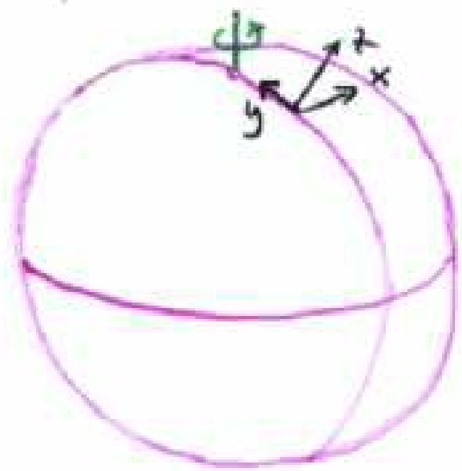
$P = 1, \ \tau = 5 \times 10^3, \ R = 10^6, \ P_m = 1$

Dynamo Oscillations, Dynamo Waves (Parker, 1955)

$\underset{\sim}{B} = \underset{\sim}{B}_p + \underset{\sim}{i}\, B\,, \quad \underset{\sim}{B}_p = \nabla \times \underset{\sim}{i}\, A\,, \qquad \underset{\sim}{u} = \underset{\sim}{\check{u}} + \underset{\sim}{i}\, U$

$$\frac{\partial}{\partial t} A = \alpha B + \lambda \nabla^2 A$$

$$\frac{\partial}{\partial t} B = \underset{\sim}{B}_p \cdot \nabla U + \lambda \nabla^2 B$$



$$(A, B) = (\hat{A}, \hat{B}) \exp\{ i q \cdot \underset{\sim}{x} + \sigma t \}$$

$$p\hat{A} = \alpha \hat{B}\,, \quad p\hat{B} = -i\,(q \times \nabla U)_x\, \hat{A} \qquad \text{with} \quad p \equiv \sigma + \lambda |q|^2$$

$$p^2 = 2 i \gamma = 2i\left(-\tfrac{1}{2}\alpha (q \times \nabla U)_x\right)$$

for $\gamma > 0$: $p = \pm(1+i)\sqrt{\gamma} \Rightarrow \sigma = -\lambda q^2 \pm \sqrt{\gamma} + i\left(\pm\sqrt{\gamma}\right)$

growth for $-\alpha(\underset{\sim}{q} \times \nabla U)_x > 2\lambda^2 q^4$, wave propagates in $-\underset{\sim}{q}$-direction

for $\gamma < 0$: $p = \pm(1-i)\sqrt{|\gamma|} \Rightarrow \sigma = -\lambda q^2 \pm \sqrt{|\gamma|} \mp i\sqrt{|\gamma|}$

growth for $\alpha(\underset{\sim}{q} \times \nabla U)_x > 2\lambda^2 q^4$, wave propagates in $\underset{\sim}{q}$-direction

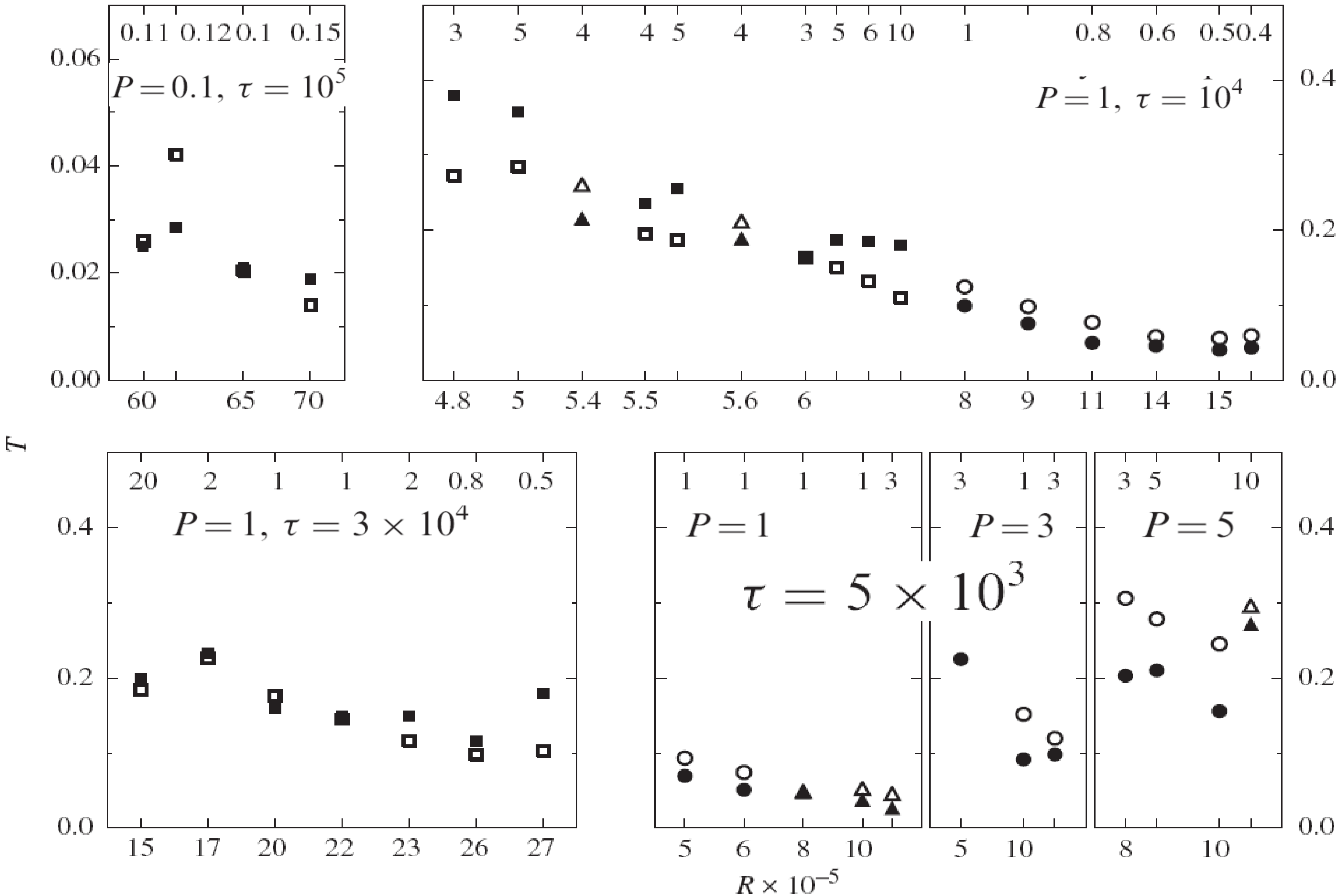
$$\alpha \equiv -\frac{\lambda}{3}\iint \frac{q^2 F(q,\omega)}{\omega^2 + \lambda^2 q^4}\, dq\, d\omega \approx -\frac{1}{3\lambda}\int q^{-2} F(q)\, dq \quad \text{with } F(q) = \int F(q,\omega)\, d\omega$$

Helicity: $H = \langle \underset{\sim}{u} \cdot \nabla \times \underset{\sim}{u} \rangle = \iint F(q,\omega)\, dq\, d\omega$ Helicity Spectrum Function F

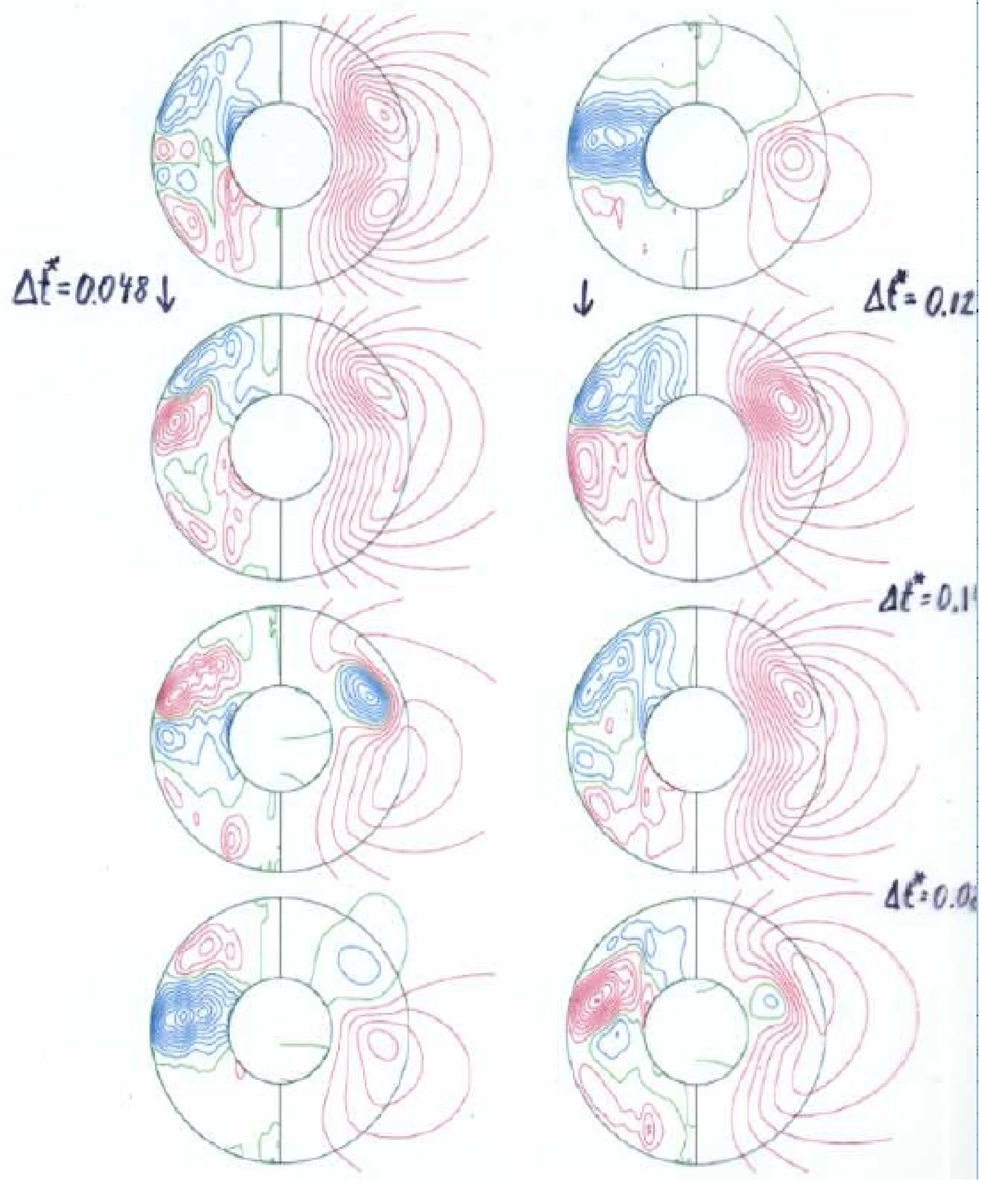
$q \approx \frac{2\pi}{d}$, $\frac{\partial U}{\partial z} \approx \frac{\nu}{d}\sqrt{2\overline{E}_{tor}}/d$, $\gamma = \omega^2 = \frac{\text{Helicity}}{3\lambda q^2}\frac{1}{2} q \frac{\partial U}{\partial z}$

$$\tilde{\omega} = \frac{d^2}{\nu}\omega \simeq \frac{1}{2\pi}\left(P_m \frac{\text{helicity}}{3} \pi \sqrt{2\overline{E}_{tor}}\right)^{\frac{1}{2}}$$

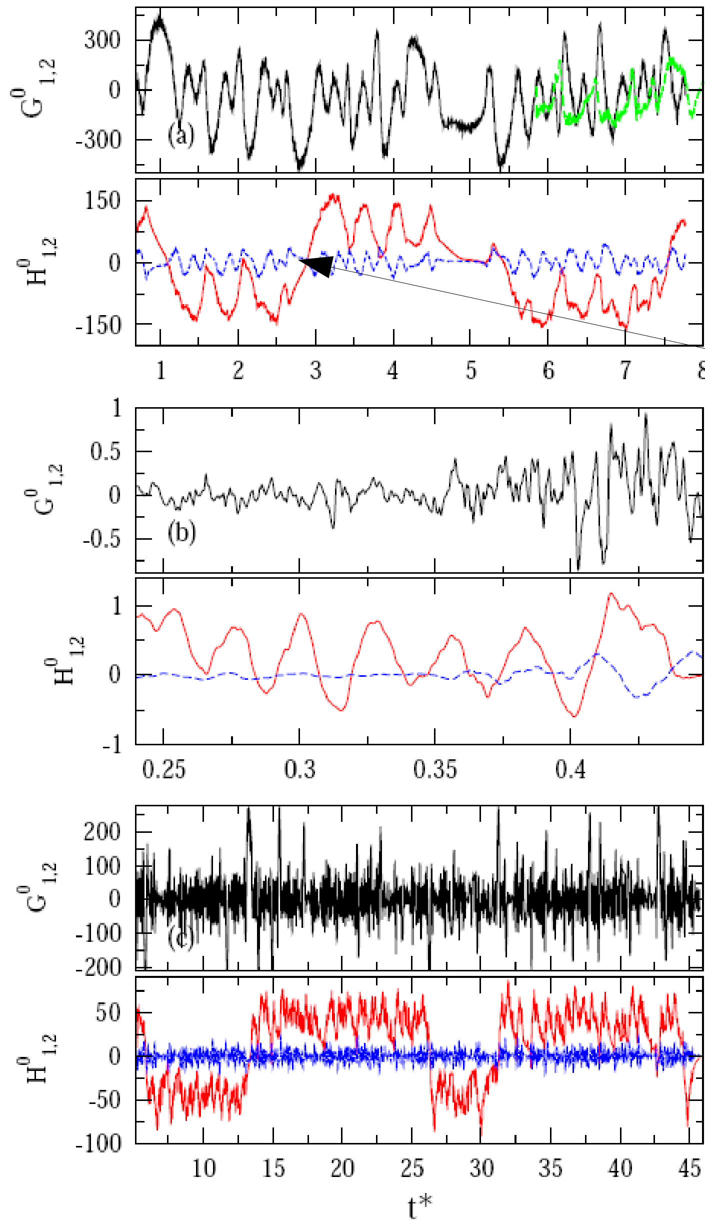
Period of oscillations: model vs. numerics



$\tau = 10^5$, $R = 4 \cdot 10^6$, $P = 0.1$, $P_m = 0.5$



Reversals cased by toroidal flux oscillations



$P = 0.1,\ \tau = 10^5$

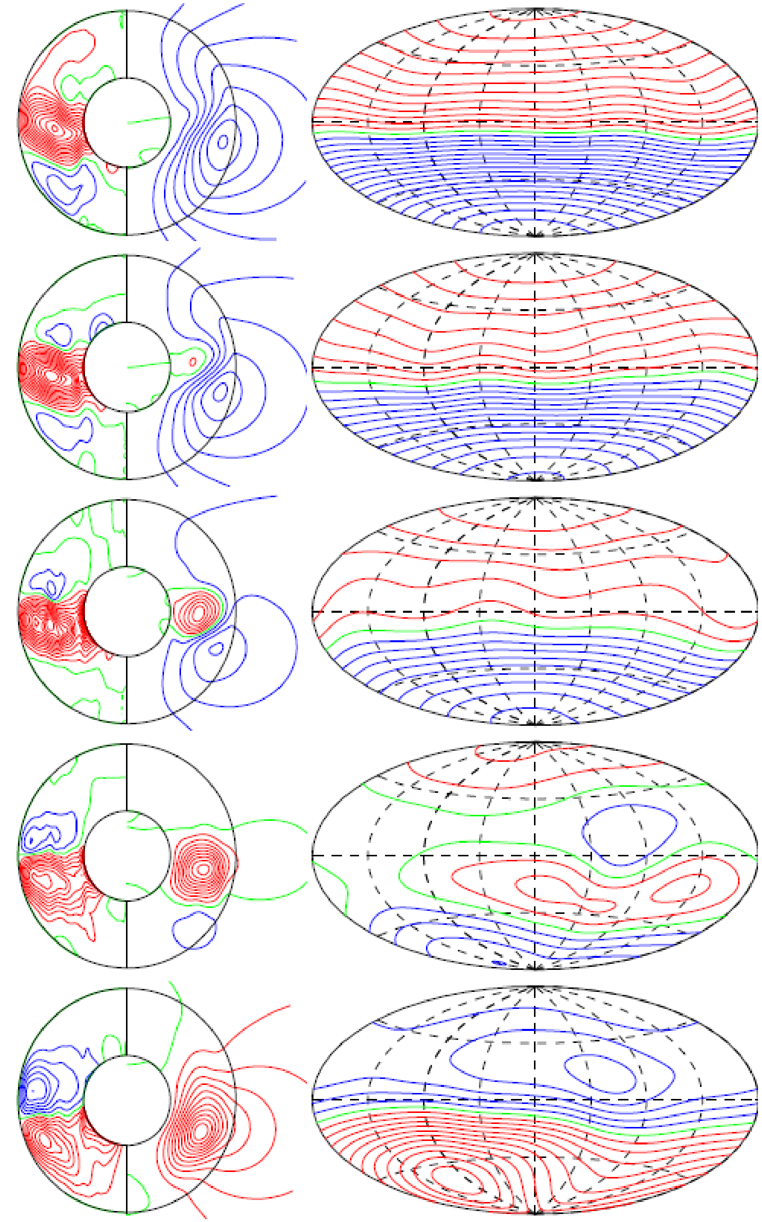
$R = 4 \times 10^6,\ P_m = 0.5$

Oscillating FD dynamo

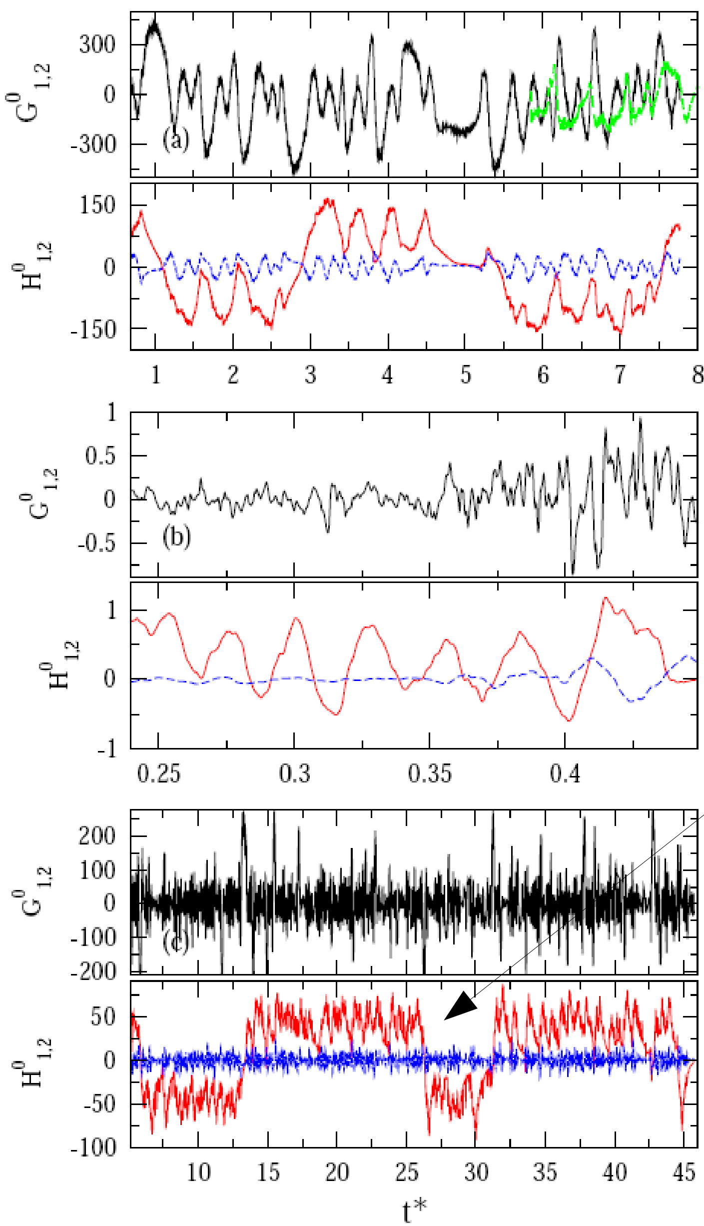
$P = 0.1,\ \tau = 3 \times 10^4$

$R = 850000 \quad P_m = 1$

Busse & Simitev, PEPI, 2008



Reversals cased by toroidal flux oscillations



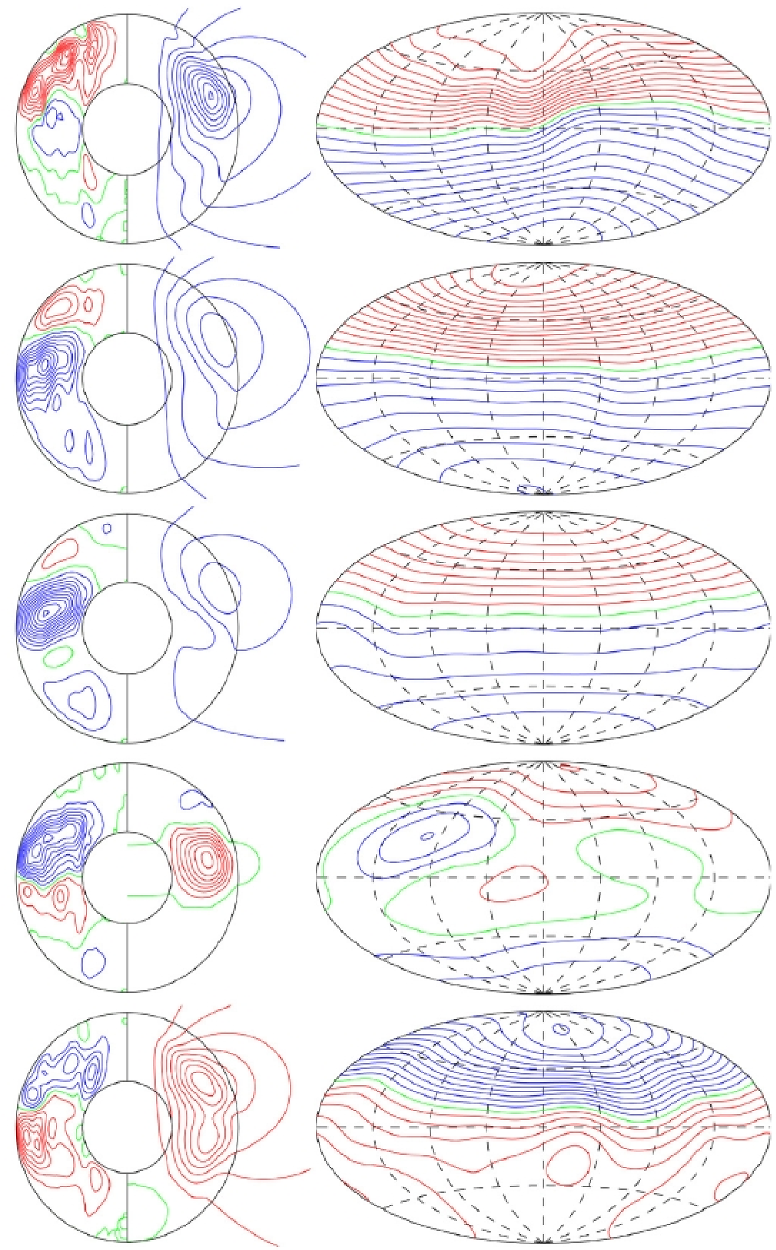
$P = 0.1,\ \tau = 10^5$

$R = 4 \times 10^6,\ P_m = 0.5$

Oscillating FD dynamo

$P = 0.1,\ \tau = 3 \times 10^4$

$R = 850000 \quad P_m = 1$



Busse & Simitev, PEPI, 2008

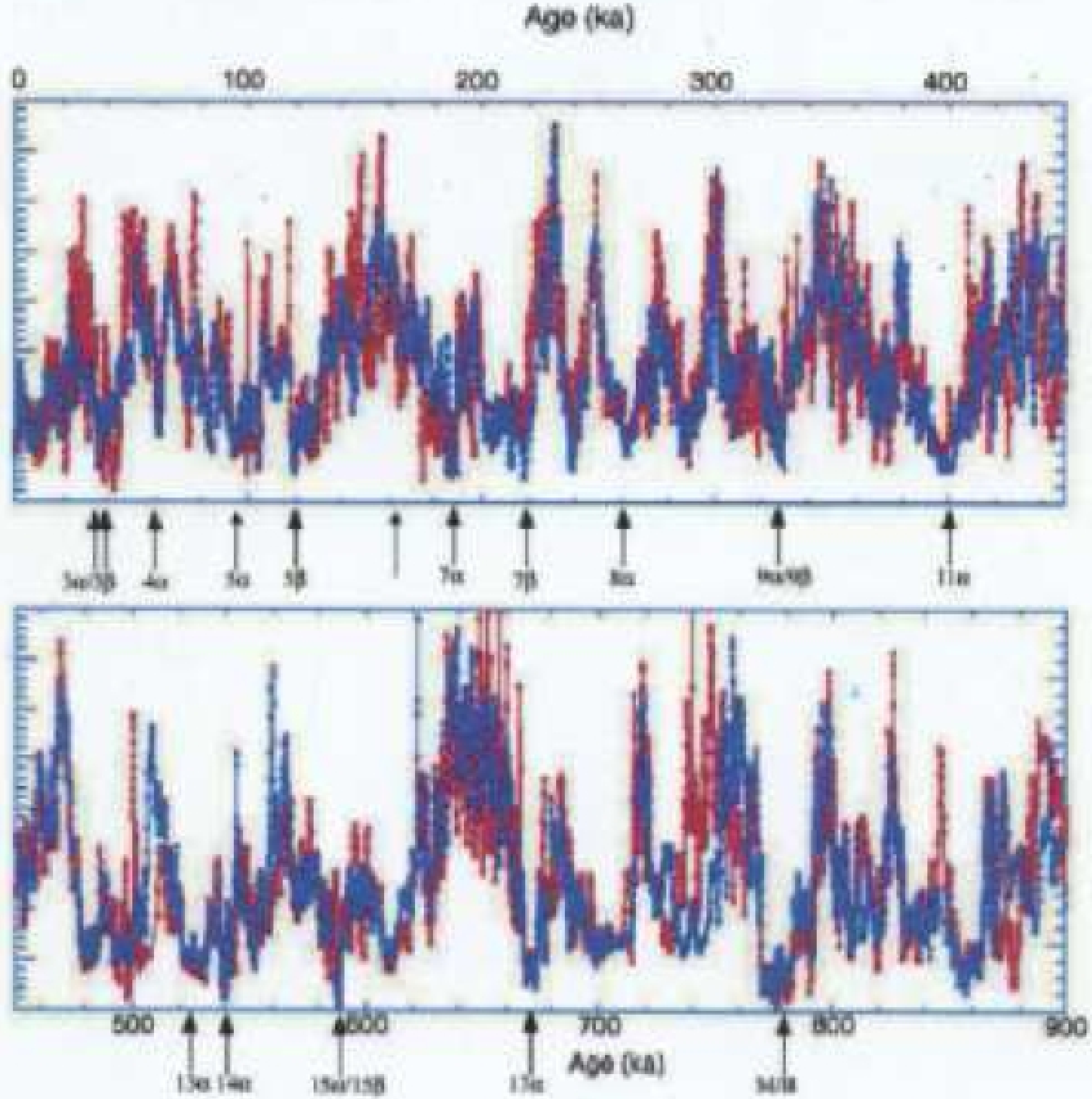
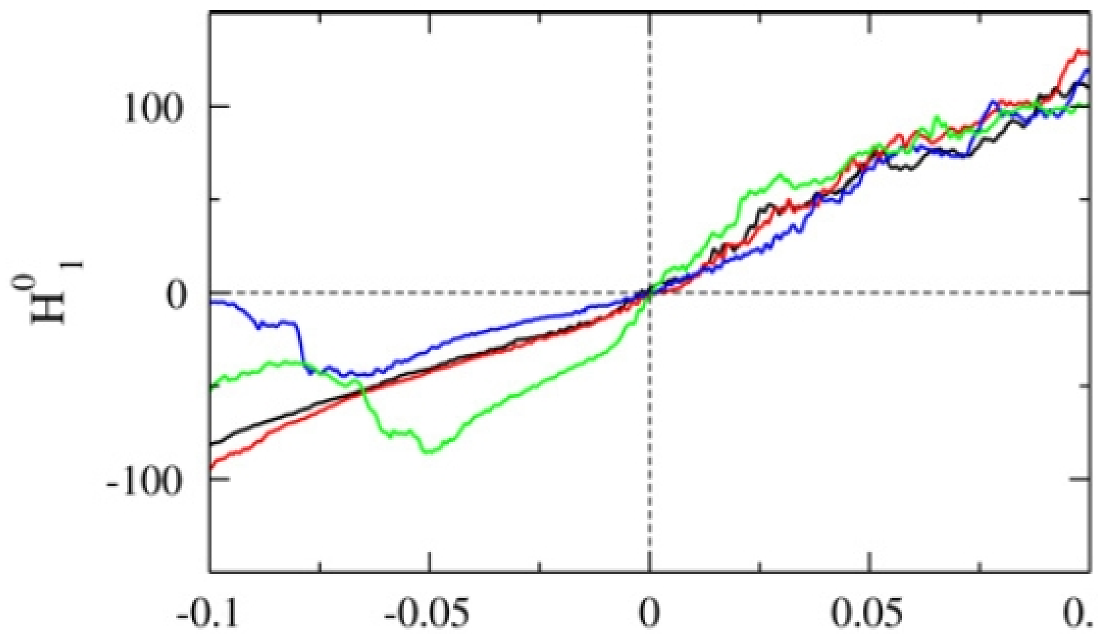


Fig. 6. Brunhes paleointensity record from ODP Sites 983/984 (Channell, 1999; Channell et al., 2004). Age models are independent and based on oxygen isotope data. Note the strong correspondence in the relative paleointensity estimates from two sites about 100 km apart. These records represent our most high-resolution evidence for overall Brunhes chron paleointensity variability. The ages of known Brunhes chron excursions (Table 1) are indicated by arrows. Note that all excursions occur in distinctive intervals of low paleointensity.

$P = 0.1,\ \tau = 10^5$

$R = 4 \times 10^6,\ P_{\rm m} = 0.5$



$P = 0.1,\ \tau = 3 \times 10^4$

$R = 850,000,\ P_{\rm m} = 1$