ISS Experiment GeoFlow: First Steps of Data Evaluation

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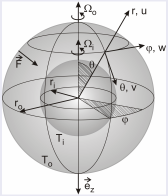
GeoFlow **experiment**: spherical Rayleigh-Bénard convection in self-gravitating force field, superposition of rotation

- radial gravity force by dielectrophoretic effect in microgravity environment of ISS
- fully spherical shell
- spherical shell convection for non-rotating case
- convection in rotating spherical shells
- $\eta = 0.5,\ Pr \approx 65,\ Ra \approx 2 \cdot 10^4,\ Ta \approx 10^6$

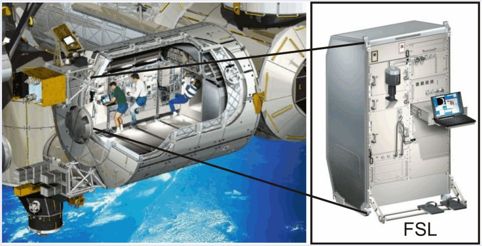


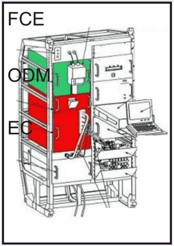
GeoFlow **experiment**: **visualization** of

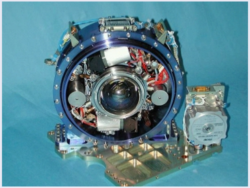
- patterns of convection for non-rotating
- and rotating spherical shells
- identification of stability of co-existing modes ($Ta = 0$)
- change of sign for drift velocities ($Ta \neq 0$)
- up to columnar cells at the tangent cylinder (Ta high)

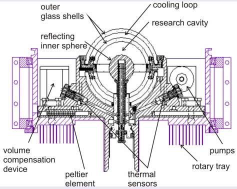
Experiment framework

- GeoFlow experiment container, integrated in Fluid Science Laboratory FSL of COLUMBUS module on International Space Station ISS
- succesful launch: Feb 7, 2008; succesful start: Aug 8, 2008; successful return: March 2009





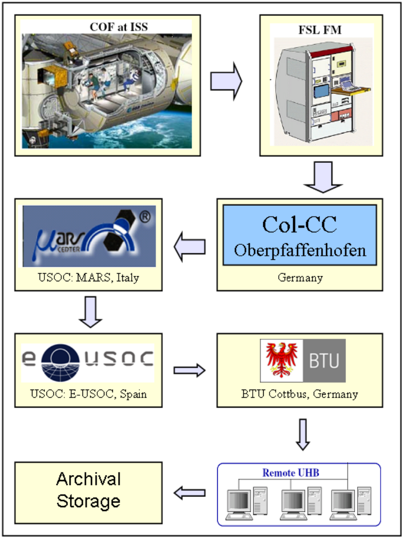




[Sources: European Space Agency (ESA); National Aeronautics and Space Administration (NASA); EADS Astrium GmbH, Friedrichshafen]

Processing and data transfer from ISS to BTU

Data transfer
ISS ⟷ BTU
Experimental data: ca. 20s
Image data: ca. 1d



Non-dimensional Boussinesq equations for dielectric convection in spherical shells, rotating reference frame, scaled to outer spherical radius

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

$$Pr^{-1}\left[\frac{\partial \mathbf{U}}{\partial t} + (\mathbf{U}\cdot\nabla)\mathbf{U}\right] = -Pr^{-1}\nabla p + \nabla^2\mathbf{U} + Ra_{centr}\cdot\frac{\eta^2}{(1-\eta)^2}\cdot\frac{1}{r^5}\,T\,\hat{\mathbf{e}}_r$$
$$-\sqrt{Ta}\,\hat{\mathbf{e}}_z\times\mathbf{U} + \widetilde{Ra}\,T\,r\sin\theta\hat{\mathbf{e}}_{eq}$$

$$\frac{\partial T}{\partial t} + \mathbf{U}\cdot\nabla T = \nabla^2 T$$

no-slip boundary conditions for velocity **U**, temperature fixed $T(\eta) = 1$, $T(1) = 0$

Parameters

geometry	radius ratio	$\eta = \frac{r_i}{r_o}$
physical prop. of fluid	Prandtl number	$Pr = \frac{\nu}{\kappa}$
dielectric buoyancy	central Rayleigh number	$Ra_{centr} = \frac{2\epsilon_0\epsilon_r\gamma}{\rho\nu\kappa}\,V_{\mathrm{rms}}^2\,\Delta T$
Coriolis force	Taylor number	$Ta = \left(\frac{2\Omega r_o^2}{\nu}\right)^2$
centrifugal force	additional Rayleigh number	$\widetilde{Ra} = \frac{\alpha\Delta T}{4}\,Ta\,Pr$

Experimental constraints

				GeoFlow	outer core	mantle
gap width	$r_o - r_i[mm]$	13.5	$\rightarrow \eta$	0.5	0.37	0.55
viscosity	$\nu[m/s^2]$	$5 \cdot 10^{-6}$	$\rightarrow Pr$	64.64	0.1-1.0	∞, viscosity temp. depend. / layered
high voltage temperature	$V_{rms}[kV]$ $\Delta T[K]$	10 ≤ 10	$\}$ Ra_{centr}	$\leq 1.4 \cdot 10^5$	$>10^{29}$	$10^6 - 10^8$
rotation rate	$n[Hz]$	≤ 2	$\rightarrow Ta$	$\leq 1.3 \cdot 10^7$	10^{30}	$<< 1$

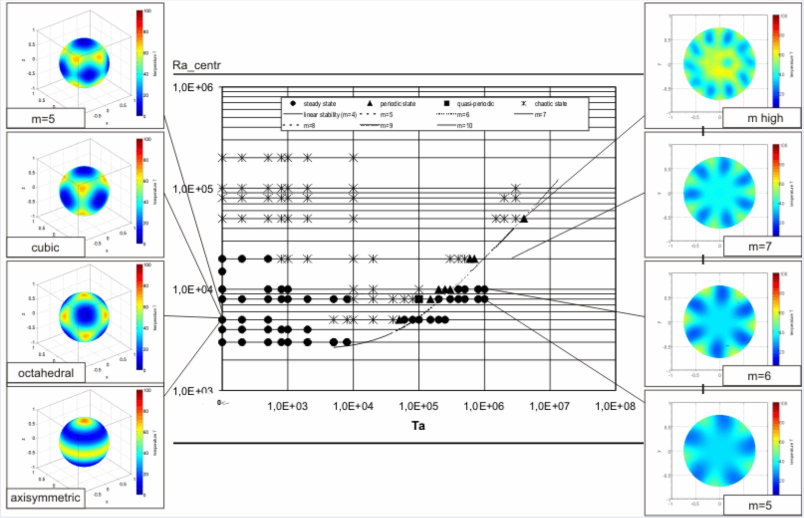
Experimental flow plan

- set-up of high voltage field:
  set-up of artificial acceleration due to central force field
- non-rotating case:
  vary ΔT resp. Ra_{centr}
- rotating case:
  set-up ΔT resp. Ra_{centr}, superimpose n resp. Ta

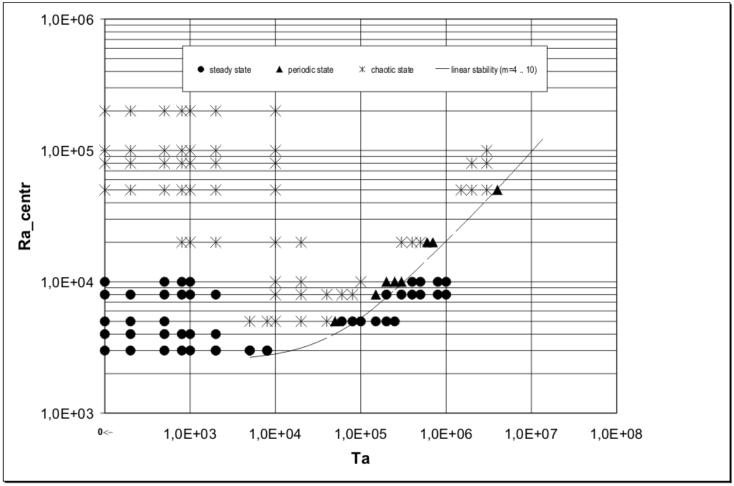
Dynamics of GeoFlow in the experimental framework

- non-rotating case
  - coexistence of several modes (axisymmetric, cubic, m=5)
  - influence of initial conditions to reach different stable states
  - transition direct from steady to irregular flow with remnant tetrahedral symmetry
- rotating case
  - change of sign for drift velocity
  - complex pattern drift
  - transition to stabilizing effects due to centrifugal forces
  - transition from steady via periodic to irregular flow

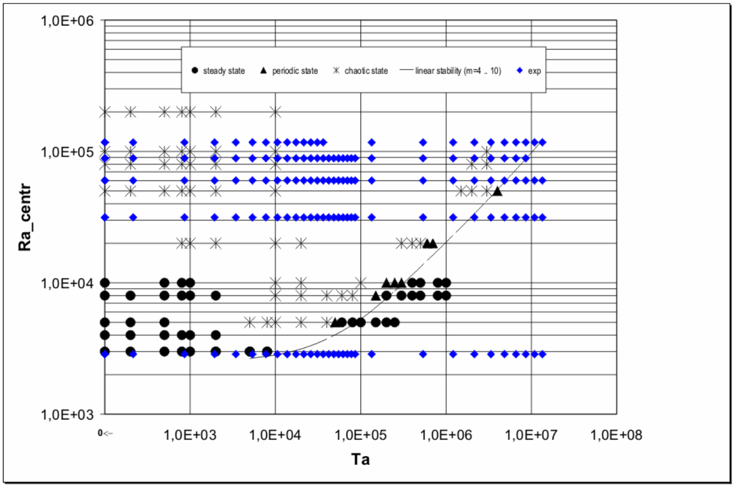
Dynamics of GeoFlow: stability diagram and flow states



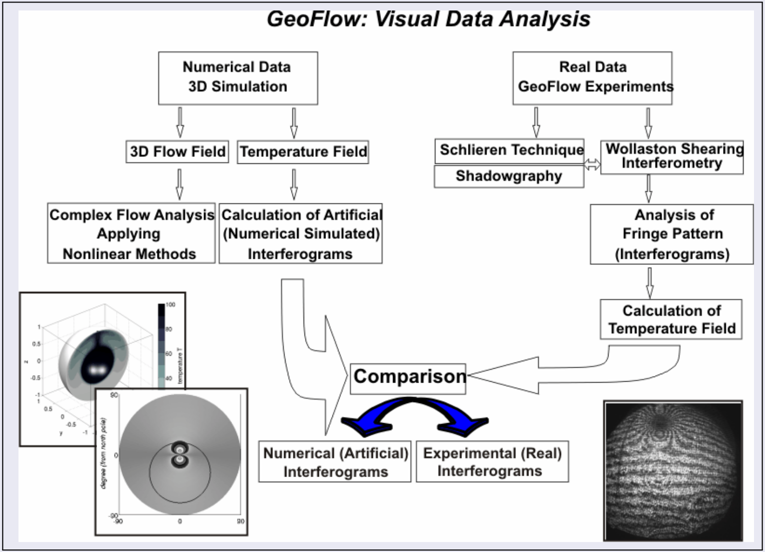
Dynamics of GeoFlow: stability diagram and flow states with first experimental runs



Dynamics of GeoFlow: stability diagram and flow states with first experimental runs

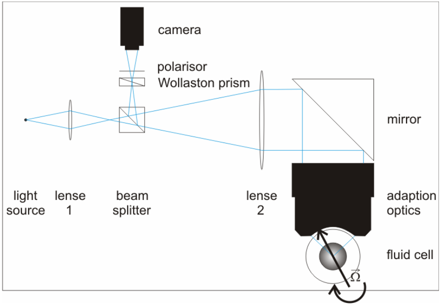


Numerical and experimental visual data analysis

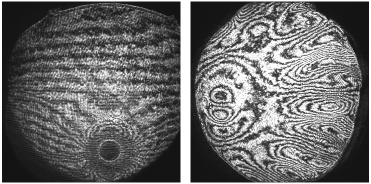


Wollaston shearing interferometry

- refractive index n=(λ,ρ,p,T) temperature gradient $\rightarrow$ density gradient $\rightarrow$ refractive index gradient
  - variation of optical path length $\rightarrow$ interference: Wollaston shearing interferometry
  - deflection of beam: Schlieren/shadowgraphy
- modular Wollaston shearing interferometer works as Schlieren/shadowgraphy

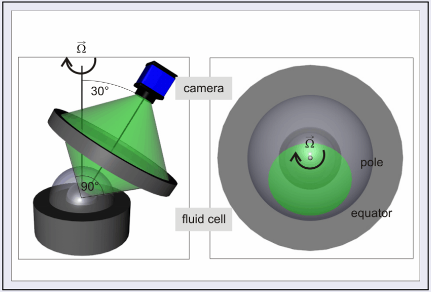


scetch of ray path



interferograms

Camera position and image view



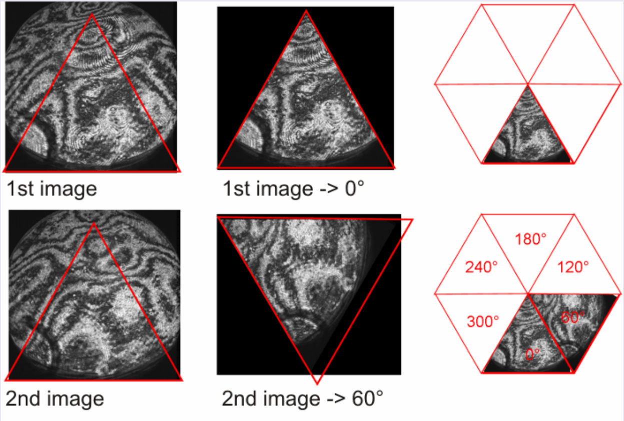
Triggering of image capture each 60°
→ 6 positions gives measurement picture of whole hemispherical surface

Data volume

images	200 GB
telemetry	50 GB

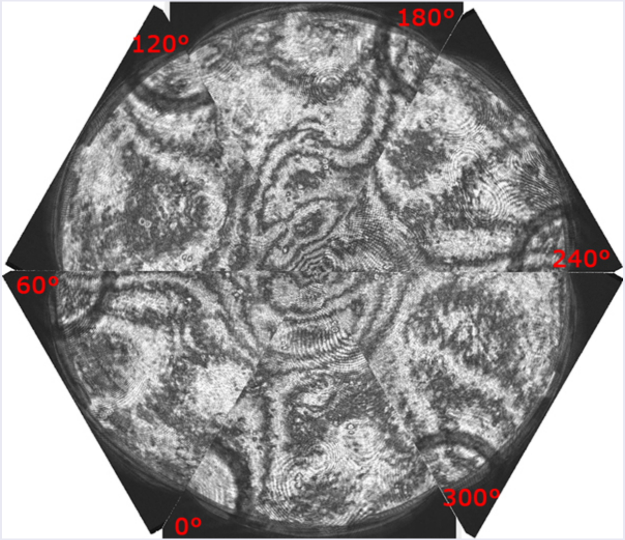
telemetry - technical values, scientific values (ΔT, μg, etc.)

Process of reconstruction of whole hemisphere in a plane

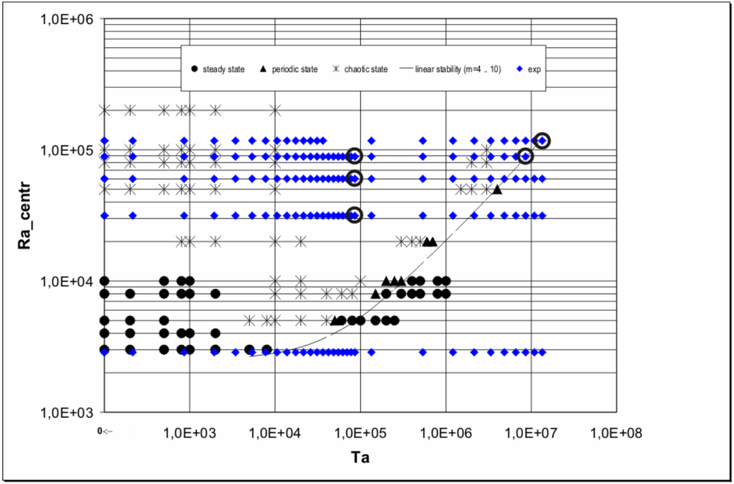


- image taken every 60° → images overlap → only a sector is visible
- defined mask (ROI) over image sequence → 6 sectors
- note: no interpolation, because of mixing fringes to gray
- note: pole is supposed to be fixed

Reconstruction of images for specific part during RUN #4

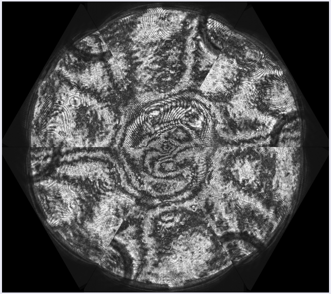


Dynamics of GeoFlow: stability diagram and flow states with first experimental runs

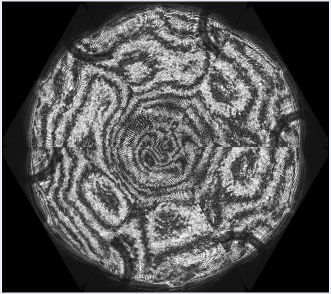


Patterns of convection in the rapid rotation regime: Alignment of convective cells at the tangent cylinder

$Ra_{centr} = 8.87 \cdot 10^4$
$Ta = 8.59 \cdot 10^6$



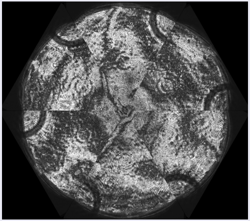
$Ra_{centr} = 1.17 \cdot 10^5$
$Ta = 1.34 \cdot 10^7$



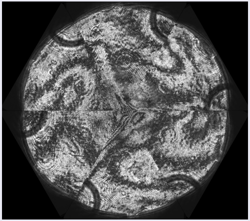
'columnar cells'

Patterns of convection in the moderate rotation regime:
Increase of thermal forcing leads to symmetry breaking bifurcations

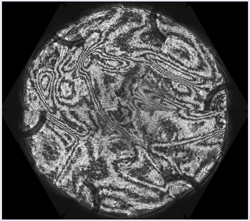
$Ra_{centr} = 3.15 \cdot 10^4$
$Ta = 8.59 \cdot 10^4$



$Ra_{centr} = 6.01 \cdot 10^4$
$Ta = 8.59 \cdot 10^4$



$Ra_{centr} = 8.87 \cdot 10^4$
$Ta = 8.59 \cdot 10^4$



Summary

- GeoFlow
  - spherical Rayleigh-Bénard convection experiment in self-gravitating force field
  - microgravity environment of COLUMBUS on ISS (Fluid Science Laboratory)
  - superposition of rotation
- dynamics for
  - non-rotating case
    - coexistence of several modes (axisymmetric, cubic, m=5)
    - transition from steady to irregular flow with dominating tetrahedral symmetry
  - rotating case
    - complex pattern drift
    - transition to stabilizing effects due to centrifugal forces
    - transition from steady via periodic to irregular flow
- first experimental data analysis shows 'columnar'-like pattern

GeoFlow I

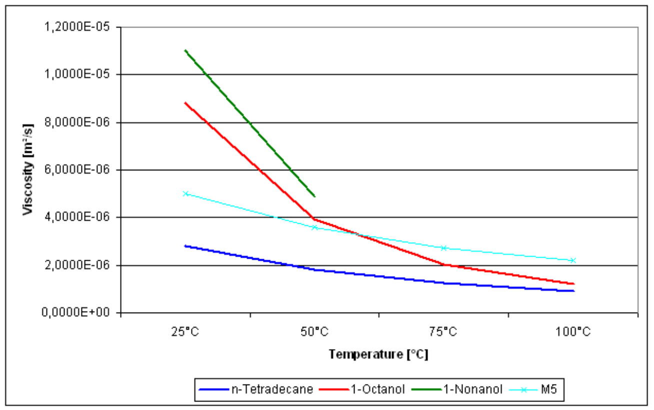
- detailed analysis of experimental data by means of image processing, fringe pattern analysis, spherical surface view, movies $\longrightarrow$ to show dynamics, which is presumed only numerically
- comparison between numerical and experimental data

GeoFlow II

- experiment on mantle convection phenomena
- experimental fluid with temperature dependent viscosity
- planned for 2010/2011

Experimental fluids filling the spherical shells system of GeoFlow I and II

- Bayer silicone oil M5 (GeoFlow I)
- alkane (paraffins) and alkanole fluids:
  Tetradecane ($C_{14}H_{30}$), Octanol (C_8H_{18O}), Nonanol (C_9H_{20O} → GeoFlow II)



Coulomb force

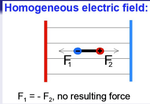
- charged particle in electric field $\mathbf{E}$
- $\mathbf{F}_\mathrm{C}(\mathbf{r}) = q\,\mathbf{E}$
- much stronger than dielectrophoretic force
- suppressed by using high-frequency AC voltage ($T_{el} \ll \tau$, τ – relaxation time of free particle)

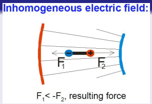
Dielectrophoretic force

- due to polarisation of medium in electric fields (local dipoles)
- $\mathbf{F}_\mathrm{D}(\mathbf{r}) = \frac{1}{2}\mathbf{E}^2(\mathbf{r})\nabla\epsilon$
- acting as a ponderomotive force only in geometrically inhomogeneous field
- resulting movement only for dieletric inhomogenous media
- depends on gradient of $\mathbf{E}$, not sign
- spherical geometry: $\mathbf{F}_\mathrm{D}(\mathbf{r}) \sim \mathbf{1}/\mathbf{r}^\mathbf{5}$
- acts as central force field (comparable to gravity)

GeoFlow constraints ...

- spherical shell system is geometrically inhomogenous
- experimental fluid is dielectric homogenous





Setting up high voltage → acceleration due to dielectric force field

$$\mathbf{g_e} = \frac{1}{2\rho}\epsilon\epsilon_r\nabla|\mathbf{E}|^2 \quad \text{with} \quad \mathbf{E} = \frac{1}{r^2}\frac{r_i r_o}{r_o - r_i}V_0\sin(\omega t)\hat{\mathbf{e}}_r$$

$$g_e = \frac{2\epsilon_0\epsilon_r}{\rho}\left(\frac{r_i r_o}{r_o - r_i}\right)^2 V_{rms}^2\frac{1}{r^5}$$

ε_0 - dielectric constant, ε_r - relative permittivity, ρ - density, V_{rms} - voltage

GeoFlow specific values ...

$$\epsilon_0 = 8.854\cdot 10^{-12}\ {}^{As}/_{Vm}, \quad \epsilon_r = 2.7,$$

$$\rho = 920\ {}^{kg}/_{m^3},$$

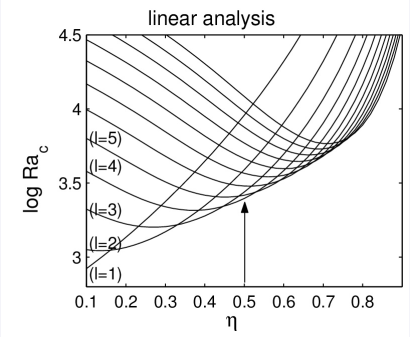
$$d = r_o - r_i = 27\ mm - 13.5\ mm = 13.5\ mm,$$

$$V_{rms} = 10\ kV$$

$$\rightarrow g_e|_{r_o} \approx 10^{-1} m/s^2 \qquad \text{compared to} \quad g \approx 10^1 m/s^2$$

→ microgravity conditions required!

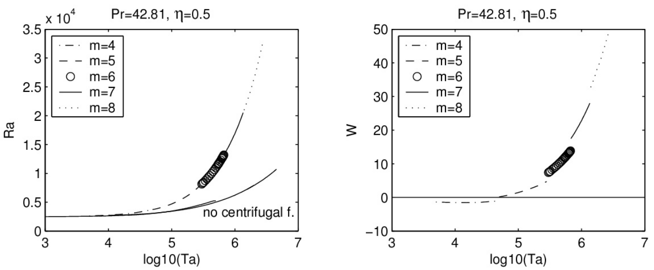
Linear analysis for $Ta = 0$



- critical Ra_{centr} for onset of convection independent on Pr
- larger $\mu \longrightarrow$ larger critical mode l

Source: V. Travnikov, C. Egbers, R. Hollerbach. *The GEOFLOW experiment on ISS. Part II: Numerical simulation*. Adv. Space Res. 32 (2003), 181–189
V. Travnikov: *Thermische Konvektion im Kugelspalt unter radialem Kraftfeld*, Dissertation, Cuvillier Verlag Göttingen, 2004

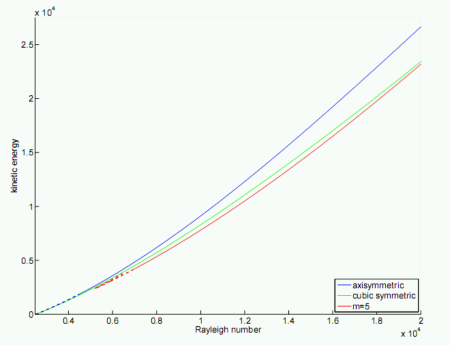
Linear analysis for $Ta \neq 0$



- shape of stability curves nearly independent on *Pr*
- instability due to Hopf bifurcation
- for large *Ta*: $Ra_{centr} \sim Ta^{2/3}$
  [P.H. Roberts. On the thermal instability of a rotating-fluid sphere containing heat sources. Philos. Trans. R. Soc. London 263 (1968), 93-117]
- drift velocity W changes sign (slows down or fastens rotation)

Source: Travnikov et al. (2003), Travnikov (2004)

Path-following analysis for stationary solutions at $Ta = 0$



- existence of multistability (axisymmetry, cubic, $m = 5$)
- sudden onset of chaos at $Ra > 28000$
- hysteresis behaviour of the chaotic branch resulting in frozen states with tetrahedral symmetry

Source: K. Bergemann, L. Tuckerman, F. Feudel. *GeoFlow: On symmetry-breaking bifurcations of heated spherical shell convection.* J. Phys.: Conf. Ser. **137** (2008), 012027 (4pp)
K. Bergemann: *Konvektion im Kugelspalt: Numerische Untersuchung und Bifurkationsanalyse am Beispiel des GeoFlow-Experimentes*, Diplomarbeit, Universität Potsdam, 2008