The GEOFLOW experiment on ISS:

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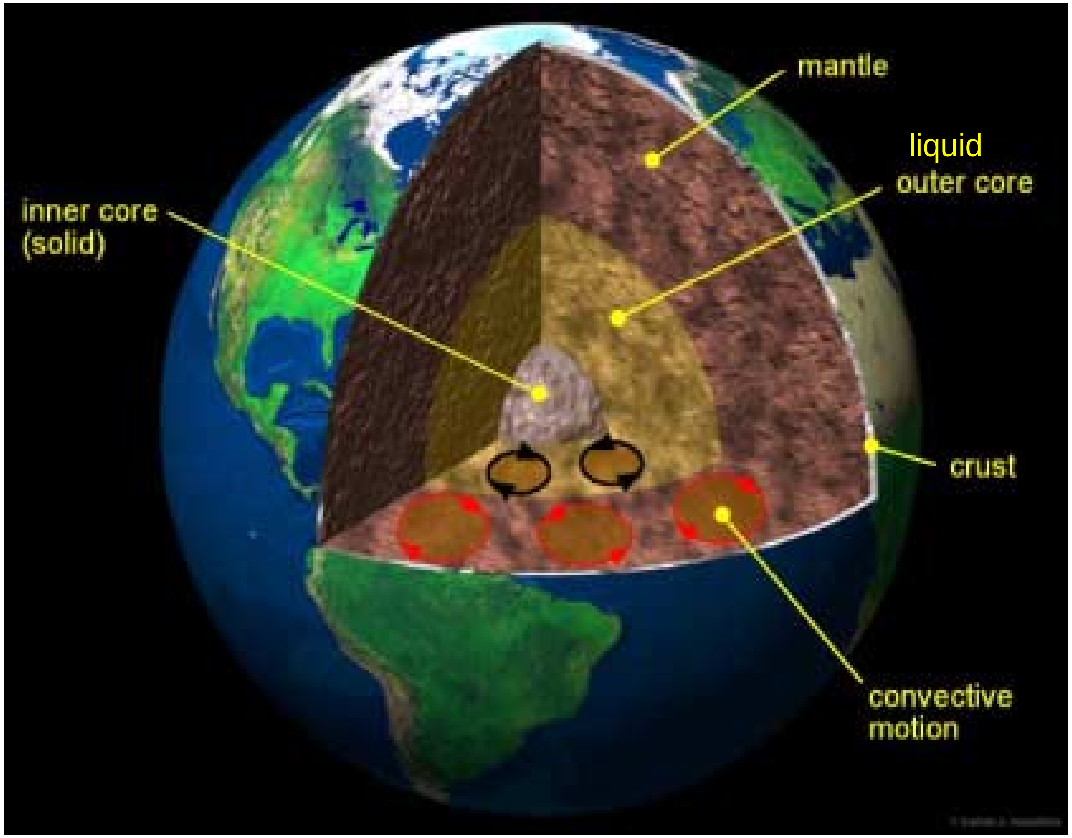

OUTLINE

- Motivation
- Physical Model
- Preparatory studies
- Topical Team activities
- GEOFLOW-EC on ISS

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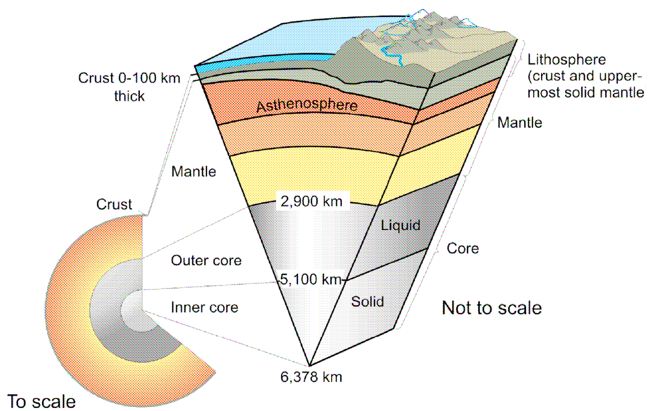
Geophysical motions: Motivation (I)

Convection occurs in the outer liquid core due to density-instabilities:
$\rightarrow$ generation of the earth´s magnetic field (dynamo-theory)
$\rightarrow$ influence on the reversals of the magnetic pole

chemical drive:
-phase-change solid-liquid
-change of the chemical composition

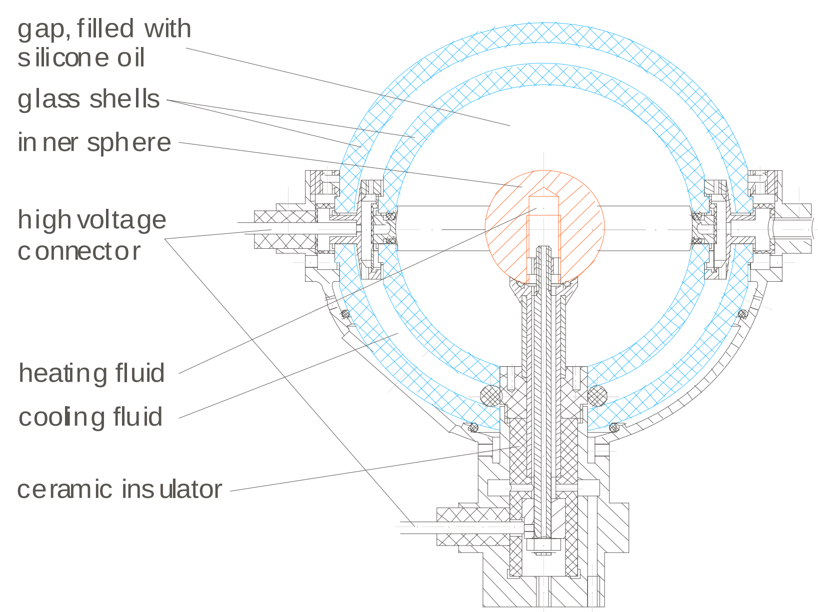
thermal drive:
-heat from radioactive decay
-heat from solidification
-internal heat of the inner core

Properties of the outer liquid core:
- coriolis-forces >> viscous- or buoyancy-forces
- high Reynolds-numbers, differential rotation?
- low Prandtl numbers
- Lorentz-force ($\Leftrightarrow$ magnetic field)



From: Kious & Tilling, 1996

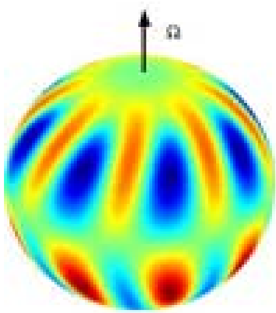
Model system: spherical gap flow



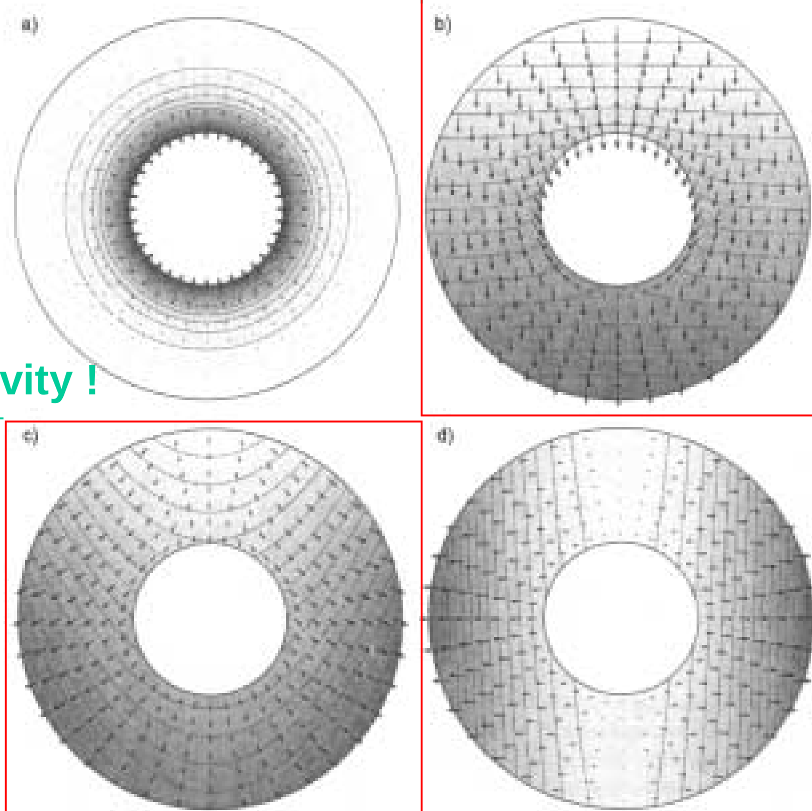
Geophysical motions: Motivation (II)

Problem: Experiments on convection in spherical shells with geophysical applications need central (artificial) gravity field

Dielectrophoretic force
(ideal central force field)



Microgravity !



Dielectrophoretic force
+ axial gravitation

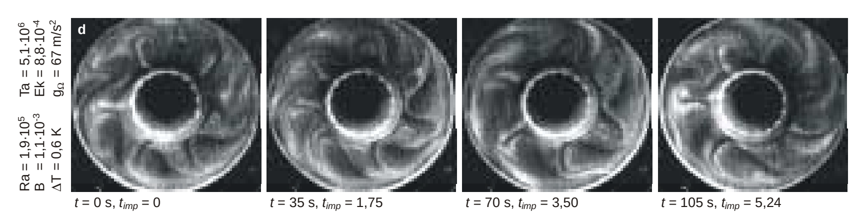
No analogy !

Centrifugal force
+ axial gravitation
(moderate rotation)

No analogy !

Artificial force field
+ axial gravitation
(rapid rotation)

Laboratory conditions !



Sitte, M.: „Thermische Konvektion in Zentralkraftfeldern“, **Diss.**, Universität Bremen, 2004
Immohr, J.: „Sphärische Differentialinterferometrie für Raumfahrtanwendungen“, **Diss.**, Universität Bremen, 2005

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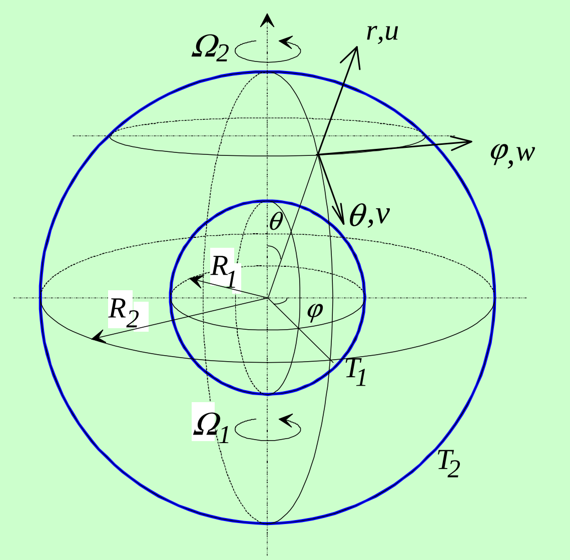
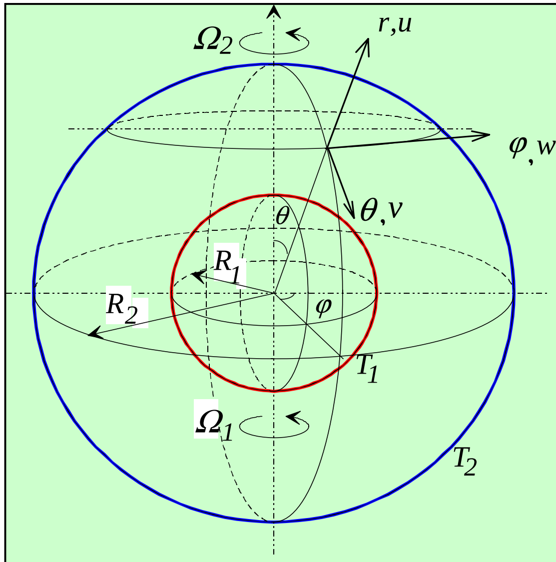
Boundary conditions of spherical gap flow model

Isothermal flows



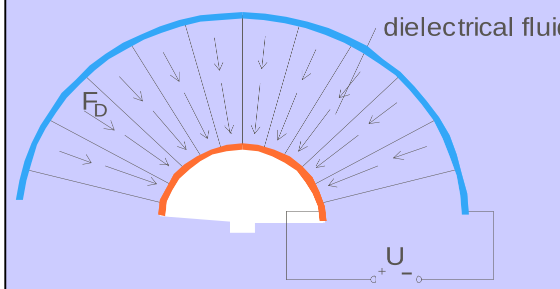
$\Omega_1 \neq 0$, $\Omega_2 = 0$; $\Omega_1 \neq 0$, $\Omega_2 \neq 0$

Natural convection



$T_1 > T_2$; g_{axial}

GEOFLOW



$$\vec{g}_{central} = \frac{2\bar{\varepsilon}}{\rho}\left(\frac{R_1 R_2}{R_2 - R_1} U_{rms}\right)^2 \frac{1}{r^5}\vec{e}_r$$

$\Omega_1 = \Omega_2 \neq 0$; $T_1 > T_2$; $g_{central}$

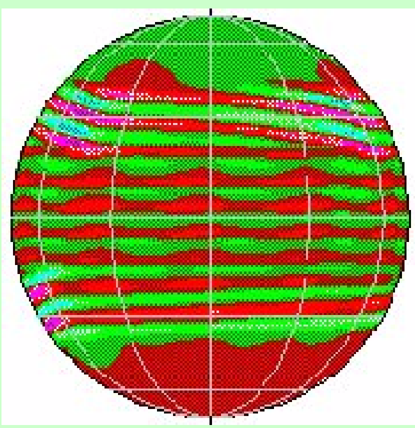
Laboratory conditions: axial gravity

Space: central gravity

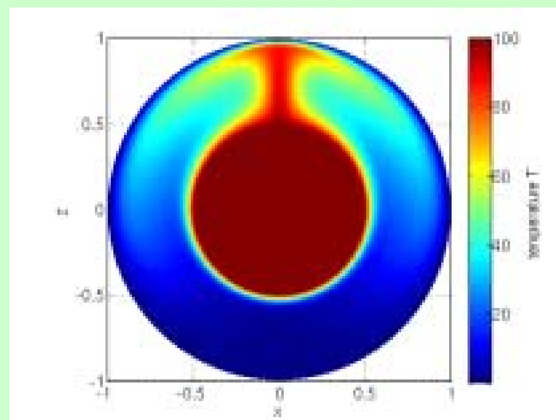
Physical model: spherical shell geometry

3D numerical simulation of spherical gap flow model

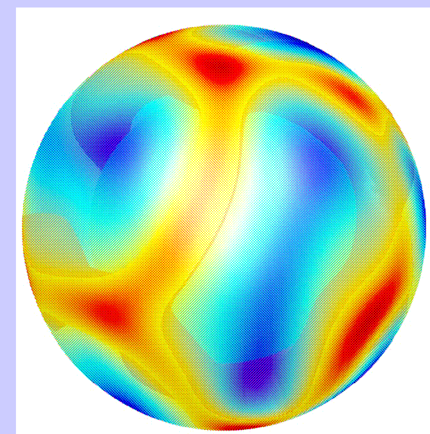
Isothermal flows	Natural convection	GEOFLOW



$\Omega_1 \neq 0$, $\Omega_2 = 0$; $\Omega_1 \neq 0$, $\Omega_2 \neq 0$



$T_1 > T_2$; g_{axial}



$\Omega_1 = \Omega_2 \neq 0$; $T_1 > T_2$; $g_{central}$

Laboratory conditions: axial gravity

Space: central gravity

Physical model: spherical shell geometry

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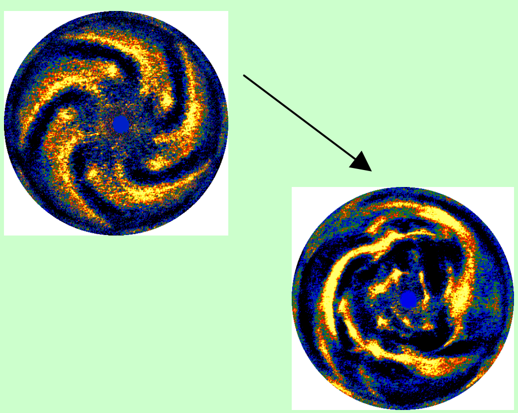
Talks on spherical gap flow model with respect to GEOFLOW

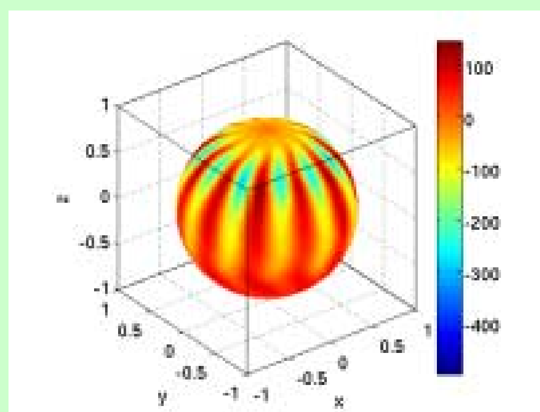
Isothermal flows

Transition to chaos in wide gap spherical Couette flow - experiment and DNS,
(D. Jilenko et al.)



Natural convection

Three-dimensional natural Convection in spherical annuli
(N. Scurtu et al.)



GEOFLOW

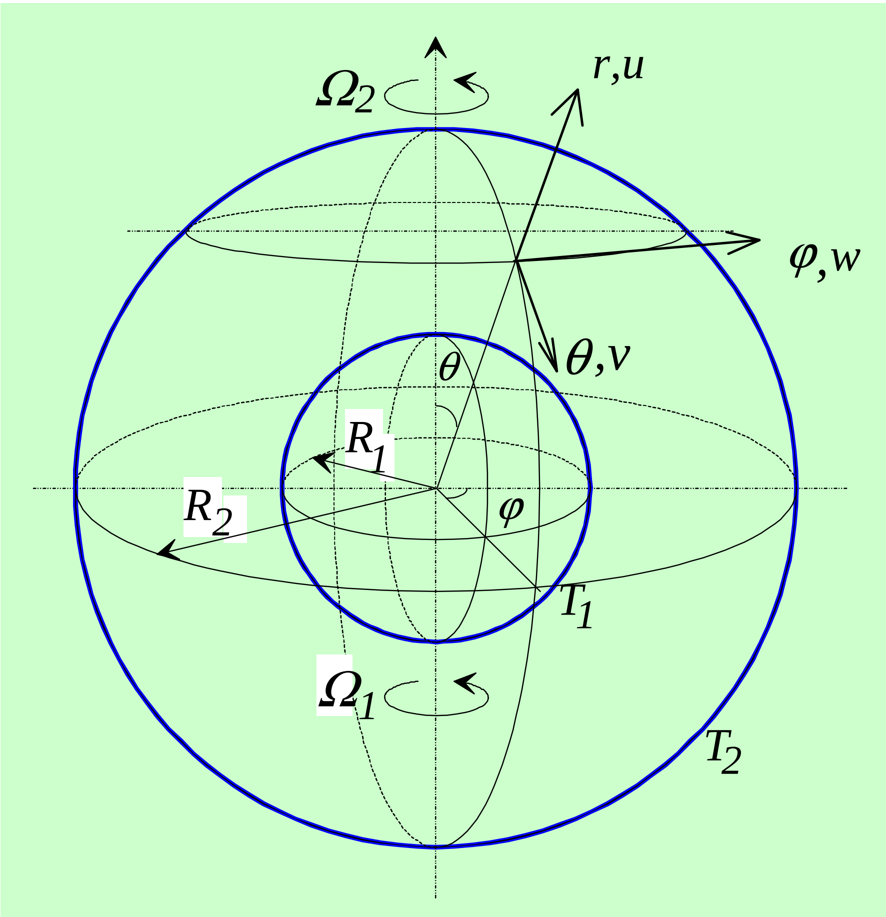
Status of experimental preparation for ISS,
(Th. v. Larcher et al.)

3D numerical simulation of supercritical convection,
(B. Futterer et al.)

Symmetry breaking bifurcations of spherical shell convection,
(K. Bergemann et al.)

Laboratory conditions: axial gravity

Space: central gravity



Incompressible viscous fluid between two independently rotating concentric spheres (working fluid: silicone oil):

Hydrodynamic equations:

- Navier-Stokes equation
- continuity equation

Control parameter:

- relative gap width $\beta = (R_2 - R_1) / R_1$
- Reynolds number $Re = (R_1^2 \Omega_1) / \nu$
- angular velocity ratio $Ro = \Omega_2 / \Omega_1$

Pattern formation (isothermal flows)

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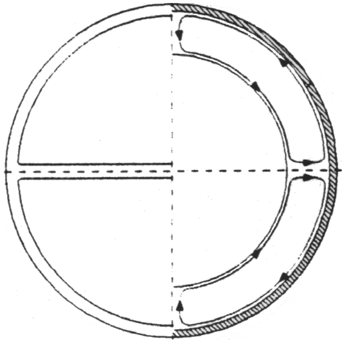
Flow structures in a spherical gap (rotation of inner sphere) during the transition to turbulence:

<u>basic state:</u>

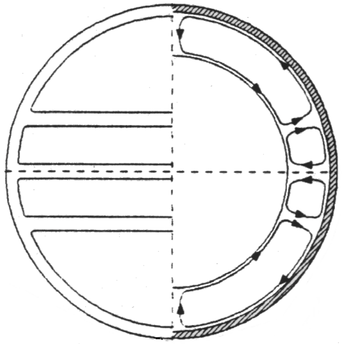
azimuthal primary flow + secondary flow in meridional plane (3D)

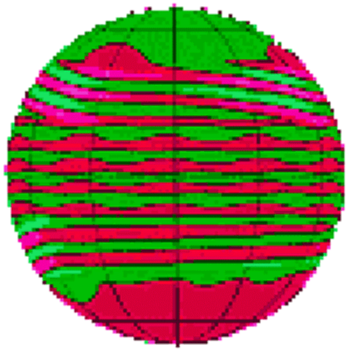


<u>supercritical flow:</u>

narrow and medium gap widths:

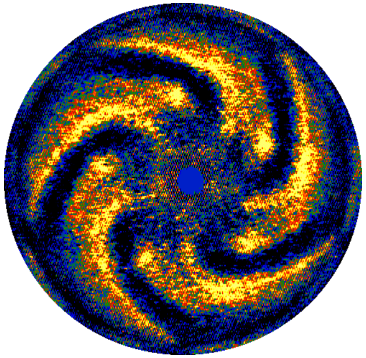
unstable for axisymmetric perturbations (centrifugal instability) instabilities:
Taylor vortices, wavy TV, turb. TV





wide gaps:

3D instability
no Taylor vortices
instability:
spiral waves



In: Egbers, Ch. & Rath, H. J.; 1995; The existence of Taylor vortices and wide-gap instabilities in spherical Couette flow.; **Acta Mechanica**, vol. 111, pp 125-140
Liu, M., Blohm, C., Egbers, Ch., Wulf, P. & Rath, H. J.; 1996; Taylor vortices in wide spherical shells.; **Phys. Rev. Lett.**, vol. 77, No. 2, pp 286-289

Instabilities and transition to chaos in wide gaps

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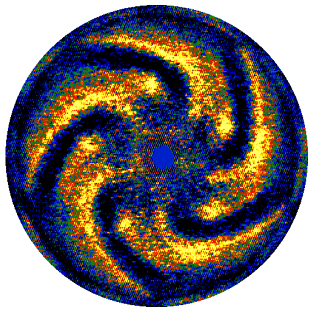
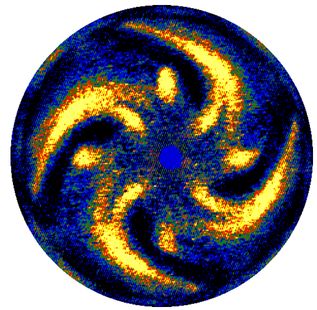
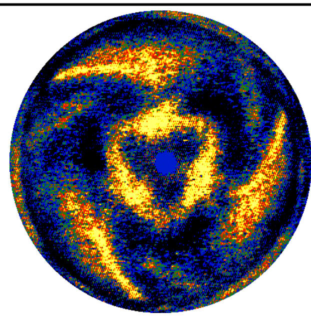


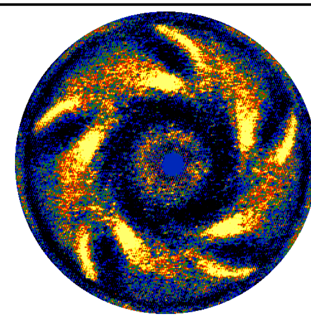
Re=1450; 5 spiral waves



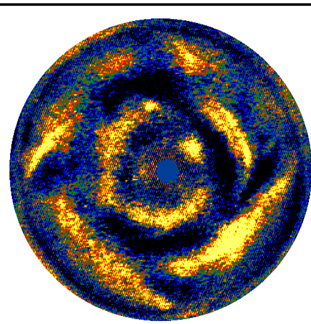
Re=1575; 4 spiral waves



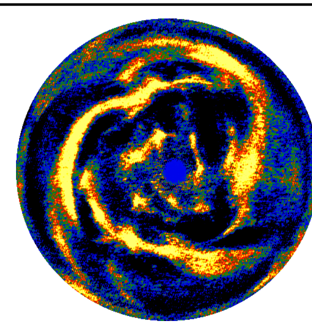
Re=1775; 3 spiral waves



Re=1875; 5 puls. spiral waves

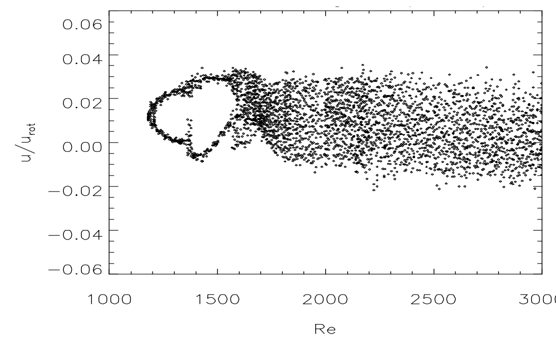


Re=2250; 4 puls. spiral waves

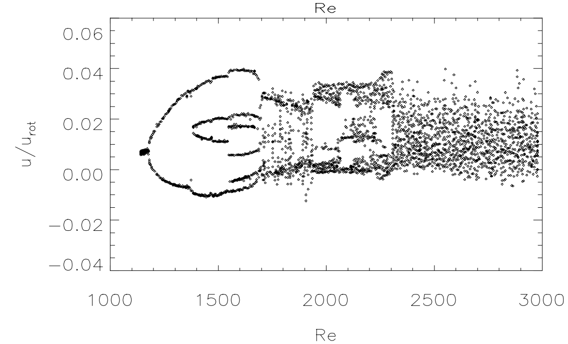


Re=3000; chaos

Bifurcation diagram (ϑ = 20°, 70°) as a function of Re (ß = 0.5)



ϑ= 20°
pole



ϑ= 70°
equator

Wulf, P., Egbers, C. & Rath, H. J.; 1999, Routes into chaos in wide gap spherical Couette flow. **Physics of Fluids**, vol. **11**, no. 6, 1359 – 1372

Egbers, C., 2004, Instabilities and bifurcation scenarios in rotating fluids, **Advances in Turbulence** (eds.: H.I. Andersson & P.A. Krogstad), CIMNE, Barcelona, Spain, 810, ISBN 84-95999-55-2

Stability diagram: 3D numerical simulation

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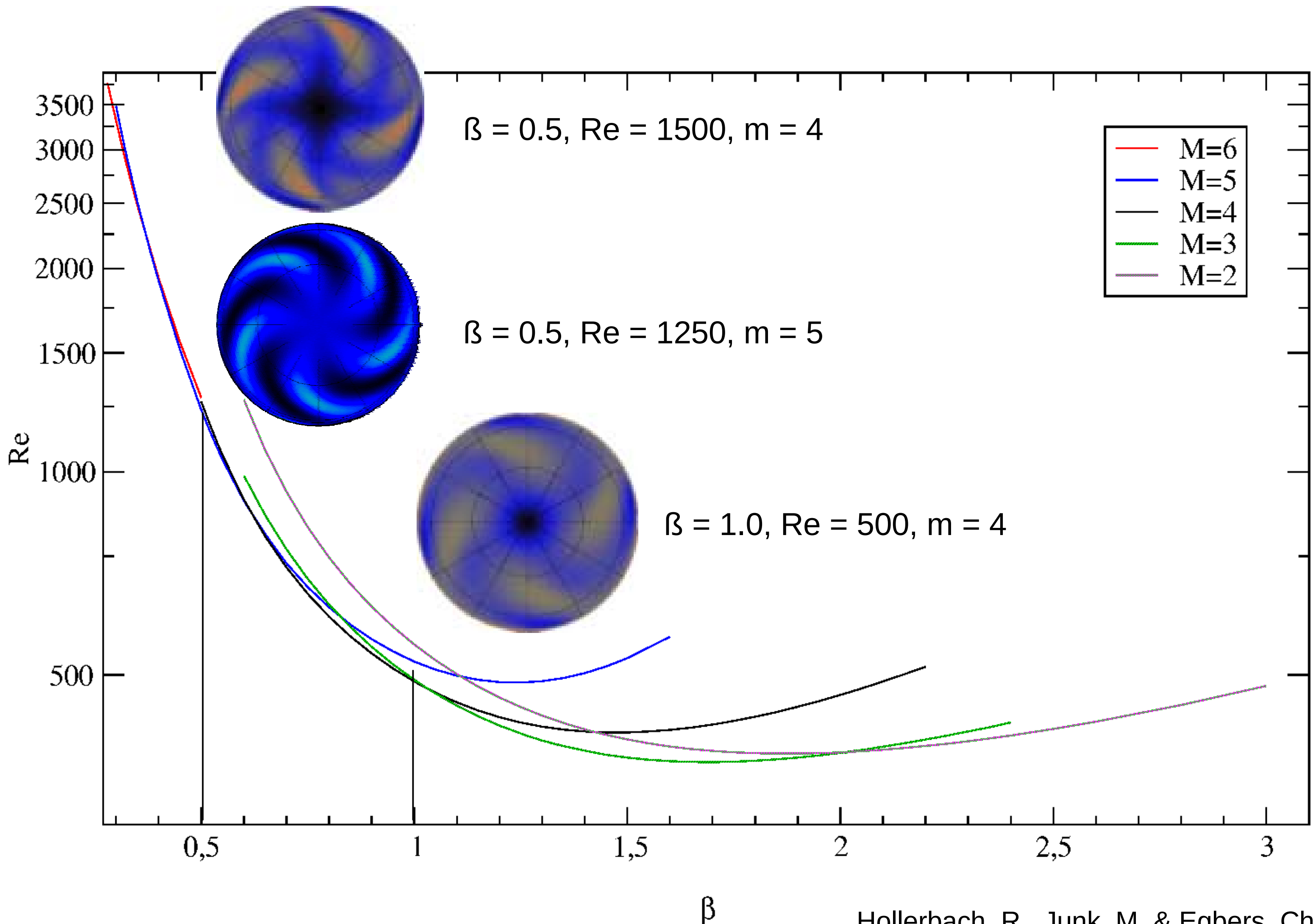
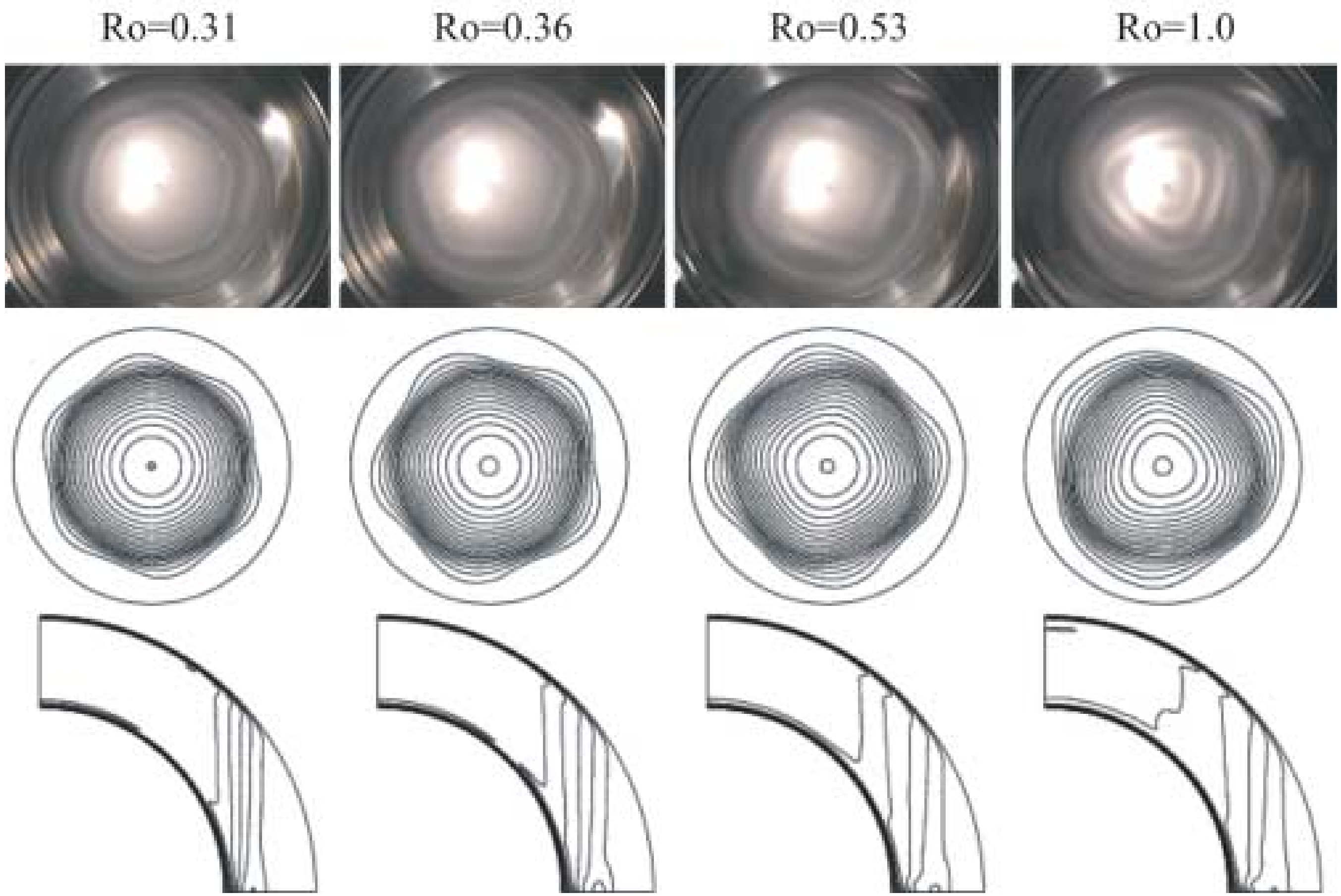


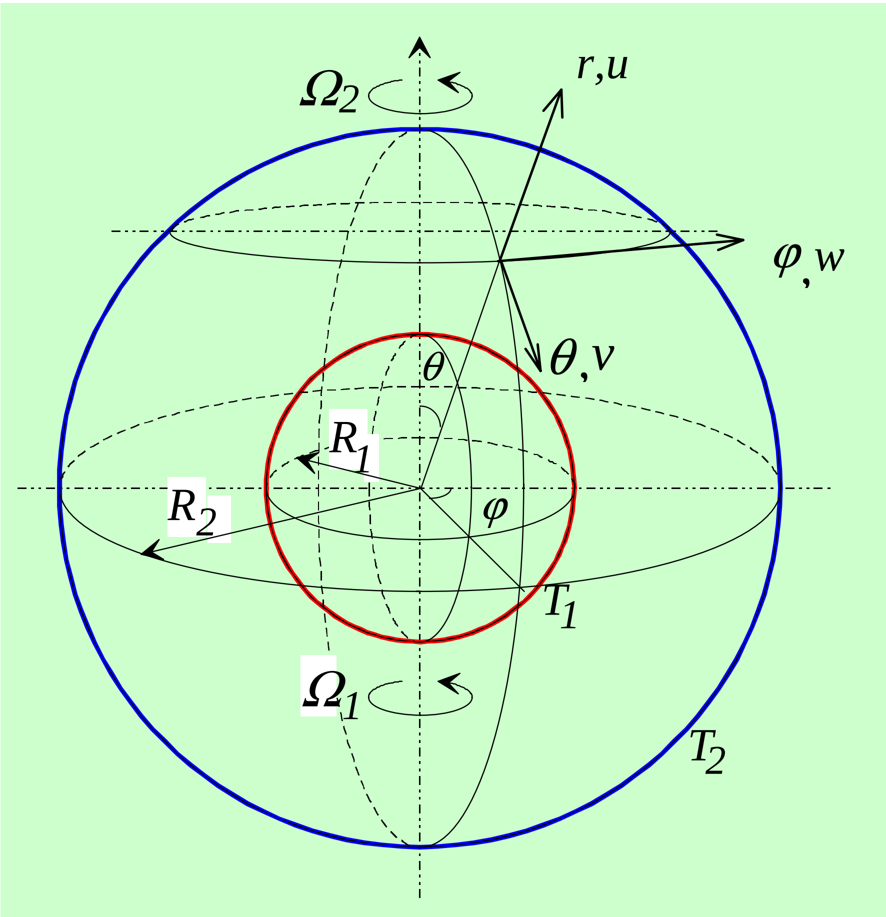
Hollerbach, R., Junk, M. & Egbers, Ch., Non-axisymmetric instabilities in wide-gap spherical Couette flow, **Fluid Dyn. Res. 38**, 257-273, 2006

Stewartson Layer



Hollerbach, Futterer, More & Egbers, Instabilities of the Stewartson Layer, Part 2. Supercritical mode transitions. **Theoretical and Computational Fluid Dynamics**, Springer, 2004

Futterer, B.: Experimentelle und numerische Untersuchung von Kugelspaltströmungen, **Dissertationsschrift**, BTU Cottbus, **VDI Fortschritt-Berichte**, Reihe 7, Strömungstechnik, Nr. 485, 2006



Incompressible viscous fluid flow between two concentric spheres **with temperature gradient** **(fluid: silicone oil)**

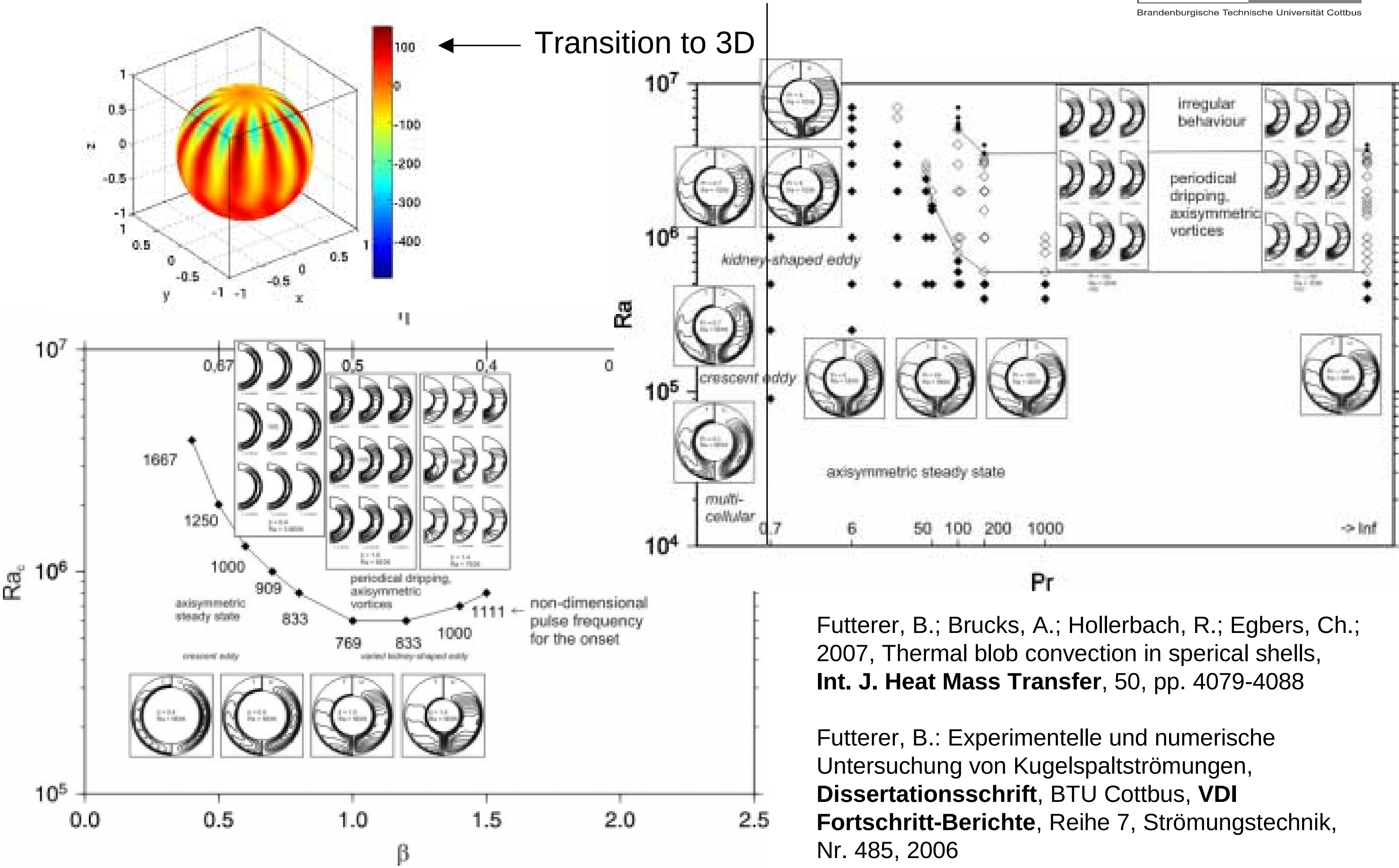
Hydrodynamic equations:

- Navier-Stokes equation
- Energy equation
- continuity equation

Control parameter:

- radius ratio $\eta = \frac{R_1}{R_2}$
- Taylor number $\mathrm{Ta} = \left(\frac{2\,\Omega\, d^2}{\nu} \right)^2$
- Rayleigh number $\mathrm{Ra} = \frac{\alpha\, g_E\, \Delta T}{\nu\, \kappa} d^3$
- Prandtl number $\mathrm{Pr} = \frac{\nu}{\kappa}$

Natural convection: stability diagrams



Futterer, B.; Brucks, A.; Hollerbach, R.; Egbers, Ch.; 2007, Thermal blob convection in sperical shells, **Int. J. Heat Mass Transfer**, 50, pp. 4079-4088

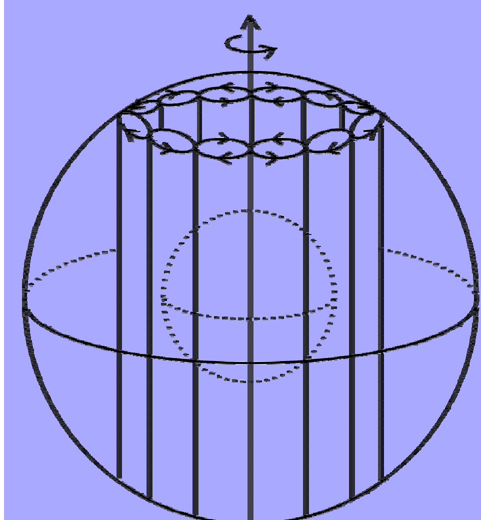
Futterer, B.: Experimentelle und numerische Untersuchung von Kugelspaltströmungen, **Dissertationsschrift**, BTU Cottbus, **VDI Fortschritt-Berichte**, Reihe 7, Strömungstechnik, Nr. 485, 2006

Convection and fast rotation (lab. exp.)

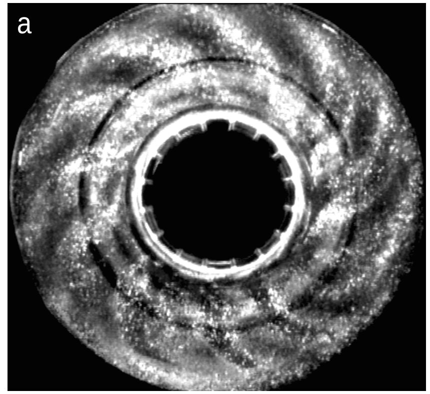
Columnar-cells

- Pr = 35
- $g_\Omega >> g$

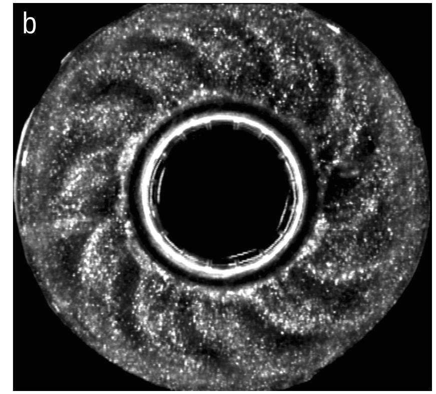
Light-sheet in equatorial plane



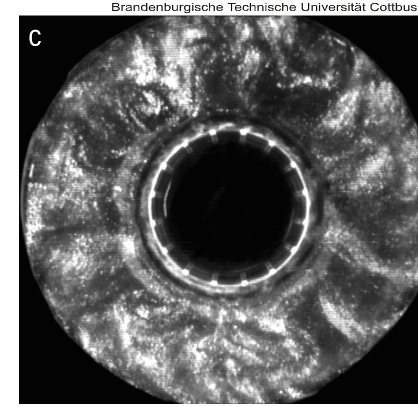
(F.H. Busse, 1970)



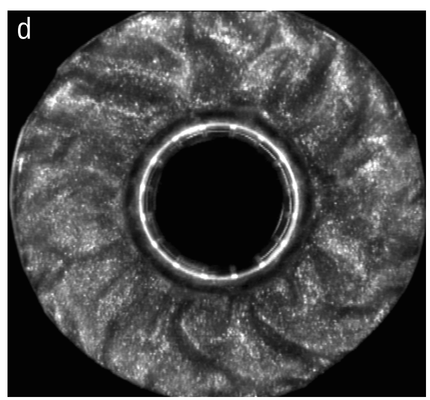
$Ra = 9{,}4\cdot10^5$ $Ta = 5{,}0\cdot10^7$
$B = 3{,}1\cdot10^{-3}$ $Ek = 2{,}8\cdot10^{-4}$
$\Delta T = 1{,}7$ K $g_\Omega = 13$ m/s^2



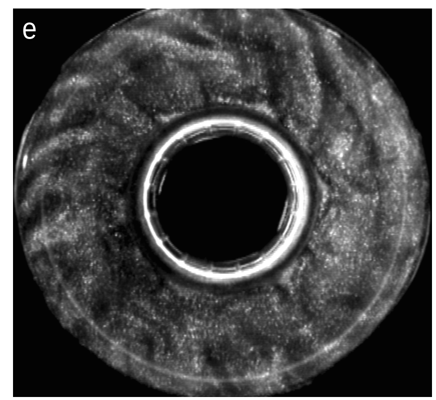
$Ra = 3{,}2\cdot10^6$ $Ta = 2{,}1\cdot10^8$
$B = 2{,}6\cdot10^{-3}$ $Ek = 1{,}4\cdot10^{-4}$
$\Delta T = 1{,}4$ K $g_\Omega = 53$ m/s^2



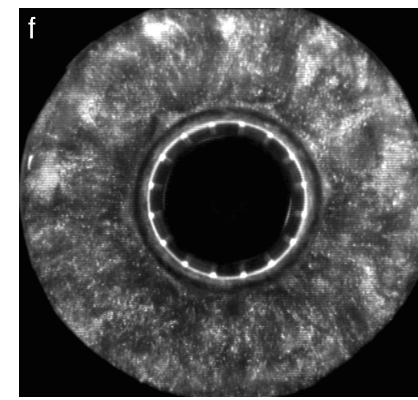
$Ra = 3{,}0\cdot10^7$ $Ta = 1{,}6\cdot10^8$
$B = 2{,}8\cdot10^{-2}$ $Ek = 1{,}6\cdot10^{-4}$
$\Delta T = 15{,}3$ K $g_\Omega = 53$ m/s^2



$Ra = 3{,}8\cdot10^7$ $Ta = 4{,}1\cdot10^8$
$B = 1{,}5\cdot10^{-2}$ $Ek = 9{,}9\cdot10^{-5}$
$\Delta T = 7{,}9$ K $g_\Omega = 119$ m/s^2



$Ra = 1{,}2\cdot10^7$ $Ta = 8{,}6\cdot10^8$
$B = 2{,}4\cdot10^{-3}$ $Ek = 6{,}8\cdot10^{-5}$
$\Delta T = 1{,}3$ K $g_\Omega = 226$ m/s^2

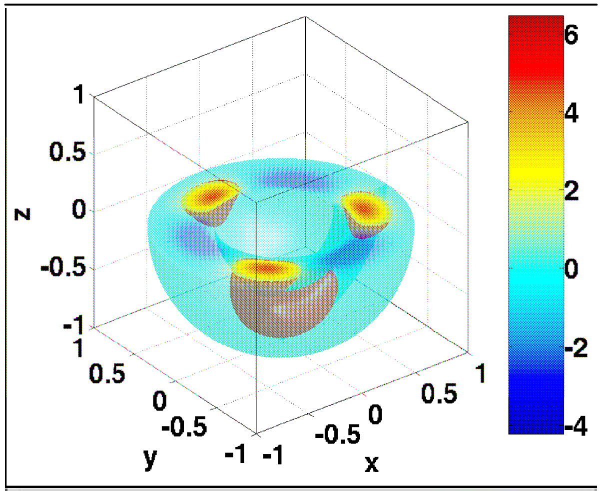


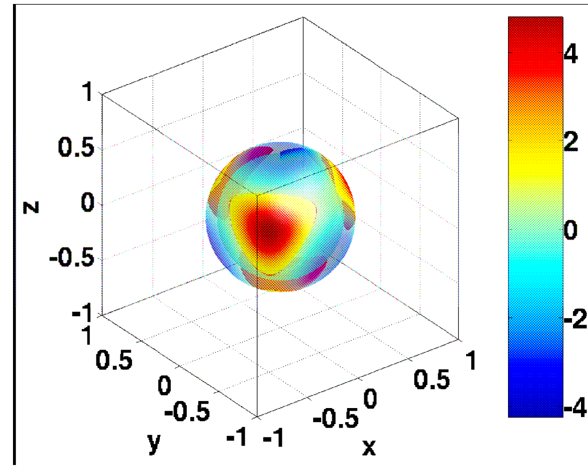
$Ra = 1{,}2\cdot10^8$ $Ta = 6{,}8\cdot10^8$
$B = 2{,}6\cdot10^{-2}$ $Ek = 7{,}7\cdot10^{-5}$
$\Delta T = 14{,}2$ K $g_\Omega = 226$ m/s^2

From: Bernd Sitte, 2004, Thermal Convection in Central Force Fields, VDI-Fortschritt-Berichte, Reihe 7, Nr. 460, Dissertation Thesis, ZARM, Universität Bremen

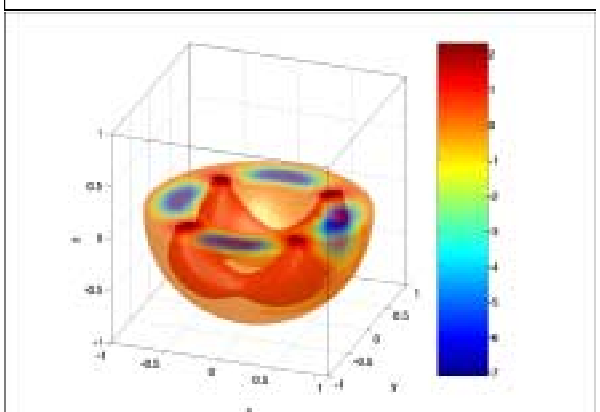
3D Convection without rotation (space exp.)

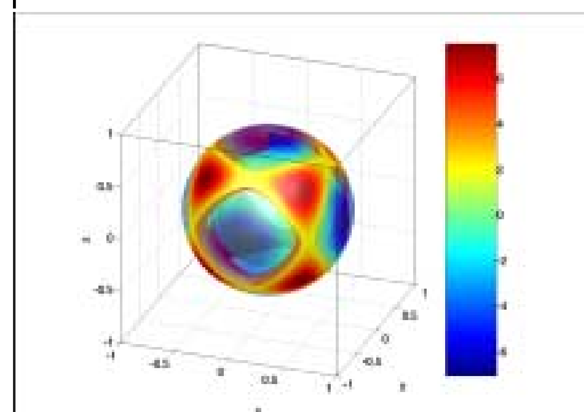
$\eta=0.4$, Pr=43, Ta = 0





Ra = $2 \cdot 10^3$
m = 3





Ra = $3 \cdot 10^3$
m = 4

velocity component u_r (equatorial plane)

velocity component u_r (radial cut)

In: Beltrame, P., Travnikov, V., Gellert, M., and Egbers, Ch., 2006, GEOFLOW: Simulation of convection in a spherical gap under central force field, **Nonlinear Processes in Geophysics**, 13, 1-11

3D Convection with rotation (space exp.)

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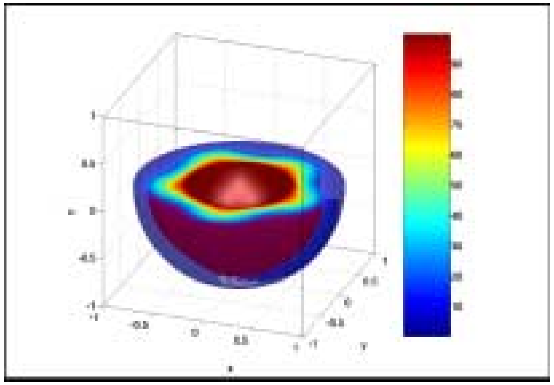
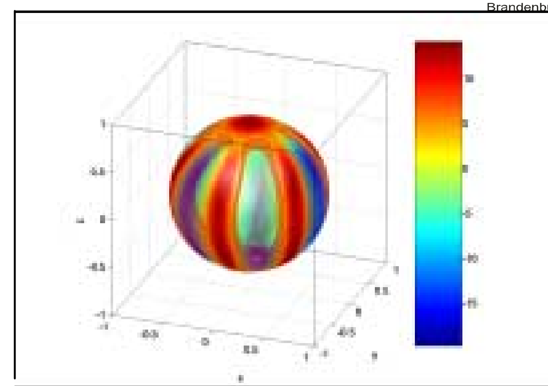


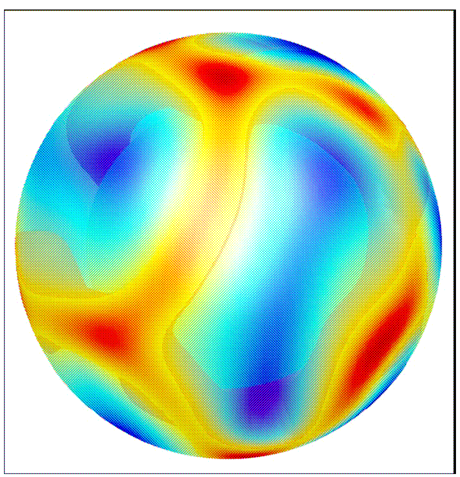
η=0.5, Pr=64

Steady states

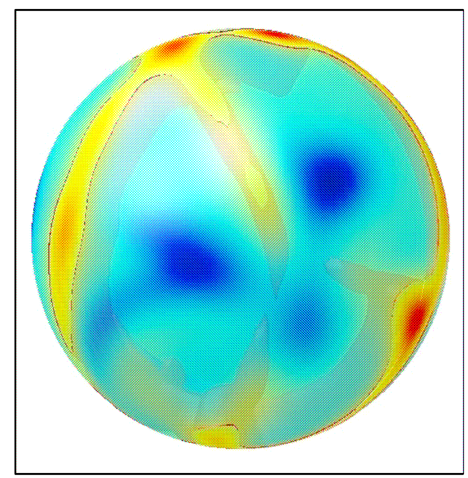


Ta = $4 \cdot 10^4$, Ra = $4 \cdot 10^3$, m = 5
temperature field T

Ta = $15 \cdot 10^4$, Ra = $8 \cdot 10^3$, m = 6
velocity component u_r in radial cut



Chaotic states



Ta = $2 \cdot 10^4$, Ra = $2 \cdot 10^4$
velocity component u_r in radial cut

Ta = $2 \cdot 10^4$, Ra = $8 \cdot 10^4$
velocity component u_r in radial cut

In: Beltrame, P., Travnikov, V., Gellert, M., and Egbers, Ch., 2006, GEOFLOW: Simulation of convection in a spherical gap under central force field, **Nonlinear Processes in Geophysics**, 13, 1-11

Topical Team and GEOFLOW project partners

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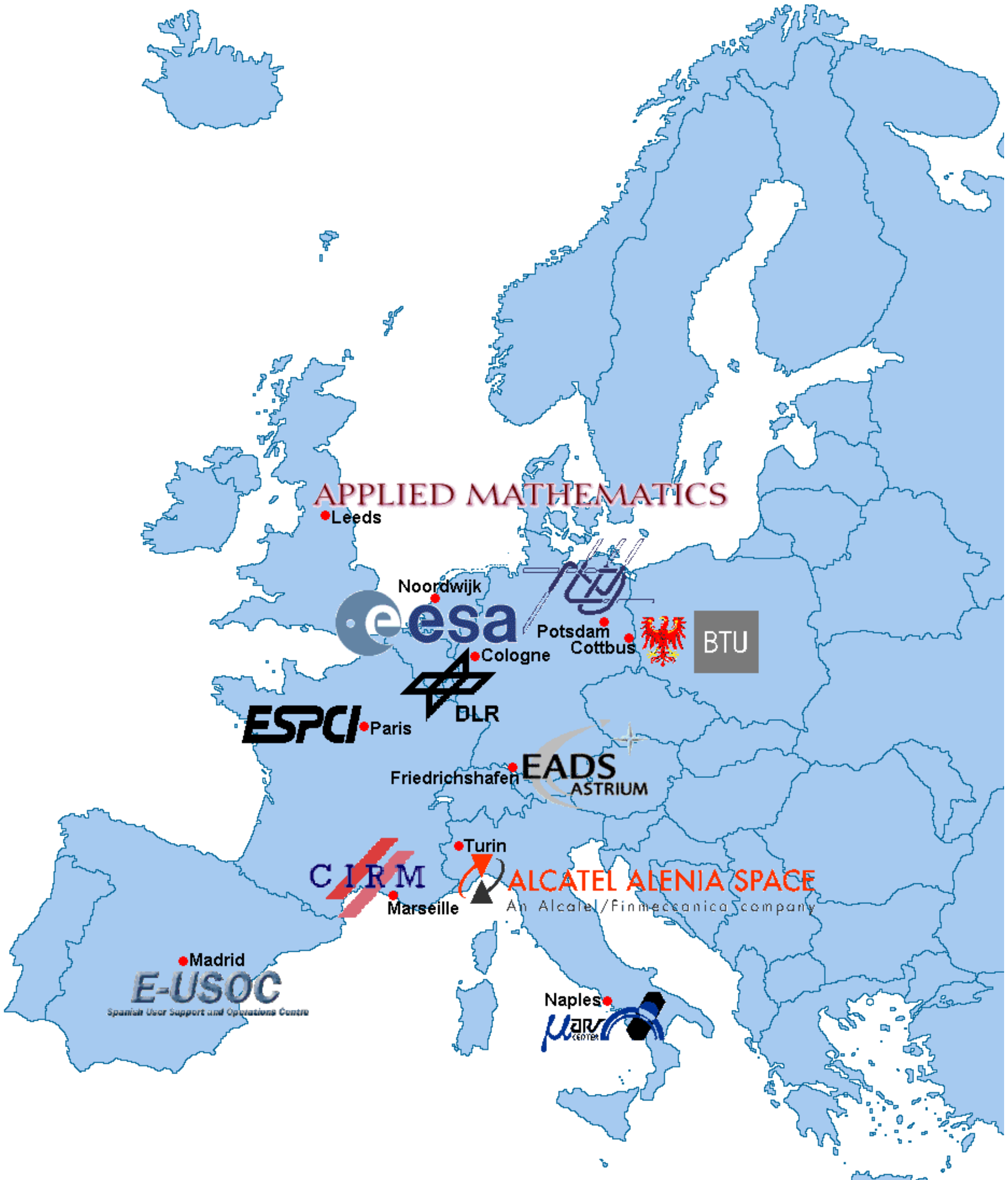

Science Team:

- BTU Cottbus, Germany
- University of Potsdam, Germany
- University of Leeds, U.K.
- CIRM, Marseille, France
- ESPCI, Paris, France

Space Industry:

- Astrium GmbH,
  Space Transportation, FN, Germany
- MARS, Naples, Italy
- Alcatel Alenia Space, Turin, Italy
- E-USOC, Madrid, Spain

Space Agencies:

- ESA, Noordwijk
- DLR, Bonn

Scientific programme of GEOFLOW (ESA AO 99-049)

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Topical Team GEOFLOW	Tasks
Team co-ordination: Christoph Egbers BTU Cottbus Germany	Preparatory experiments: • laboratory experiments on spherical gap flow model • design, parameterization and operation of ISS experiment • linear stability analysis and 3D numerical simulation of convective_flow • imaging analysis and comparison of numerical and experimental data
Rainer Hollerbach University of Leeds United Kingdom	Development of 3D numerical codes: • thermal convection with and without rotation • differential rotation • implementation of magneto-hydrodynamics in the 3D-model
Pascal Chossat CIRM Marseille France	Development of bifurcation analysis: • bifurcation analysis with and without rotation • research of mode interactions • analysis of preferred regimes, patterns, frequencies & bifurcations
Laurette Tuckerman ESPCI, Paris, France	Non-linear stability analysis: • bifurcation of time-dependent states
Fred Feudel University of Potsdam Germany	Non-linear stability analysis: • path following methods • non-linear dynamic analysis methods

Associated partners:

• ISL, St. Louis, French-German-Research Institute, Dr. Srulljes (Interferometry, Shadowgraph, Schlieren)

• Univ. DuHavre, Prof. Mutabazi (Couette-Taylor instabilities, Thermal convection, Nonlinear dynamics)

GEOFLOW on ISS (Microgravity)

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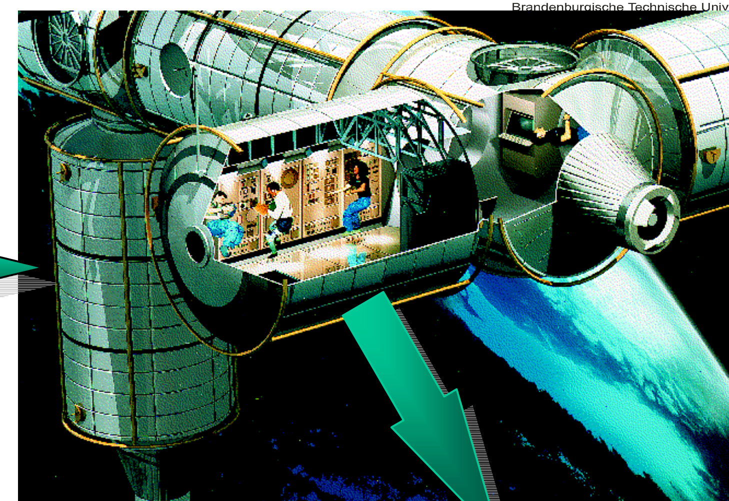
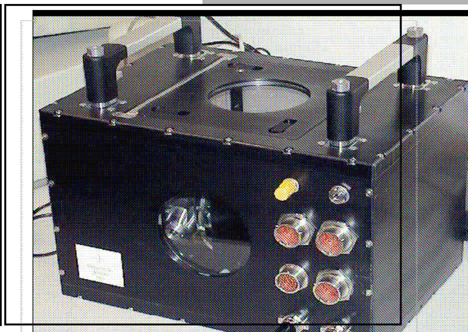
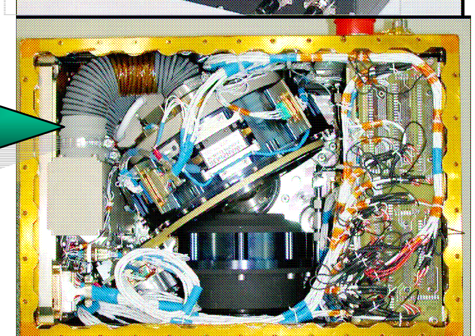


The GEOFLOW Experiment

- takes place in the European Colombus Orbital Facility (COF) on ISS
- integration as an Experiment Container (EC) in the Fluid Science Lab (FSL)



Down scaling



GEOFLOW: Time schedule / preparation

1999

- Proposal to ESA (AO-programme), international peer review

2000

- Project start (co-ordination by BTU Cottbus)
- "Kick-off-meeting for organization and planning of scientific and technical preparation (numerical simulation, laboratory models, flight model)

2002

- Build-up and testing of laboratory model ("Breadboard"), Phase A/B
- Tests with laboratory breadboard (BTU Cottbus)
- Stability analysis methods for predicting interesting flow modes

2004

- Design and build-up of "Engineering Model, EM" with GEOFLOW Container together with Space industry (EADS SpaceTransportation), Phase C/D
- Start of parameter variations and 3D-numerical simulations, supercritical flows
- Start of investigations on nonlinear dynamics of the flow

2005

- Topical Team established, Adaption to Fluid Science Laboratory (EM), first tests
- Critical Design Review (CDR); 1. TT-meeting, Paris

2006

- Build-up of "Flight Model, FM", first tests (EADS)
- 2. TT-meeting, Cottbus

2007 - 2009

- Parametrization and tests of EM-/FM-hardware, 3. TT-meeting, Friedrichshafen
- Start of COLUMBUS and GEOFLOW with Shuttle STS-1E: 9/2007 – 3/2008
- User Home Based (UHB) Data Akquisition of GEOFLOW at BTU Cottbus
- Reflight of GEOFLOW

GEOFLOW: Design & Breadboard

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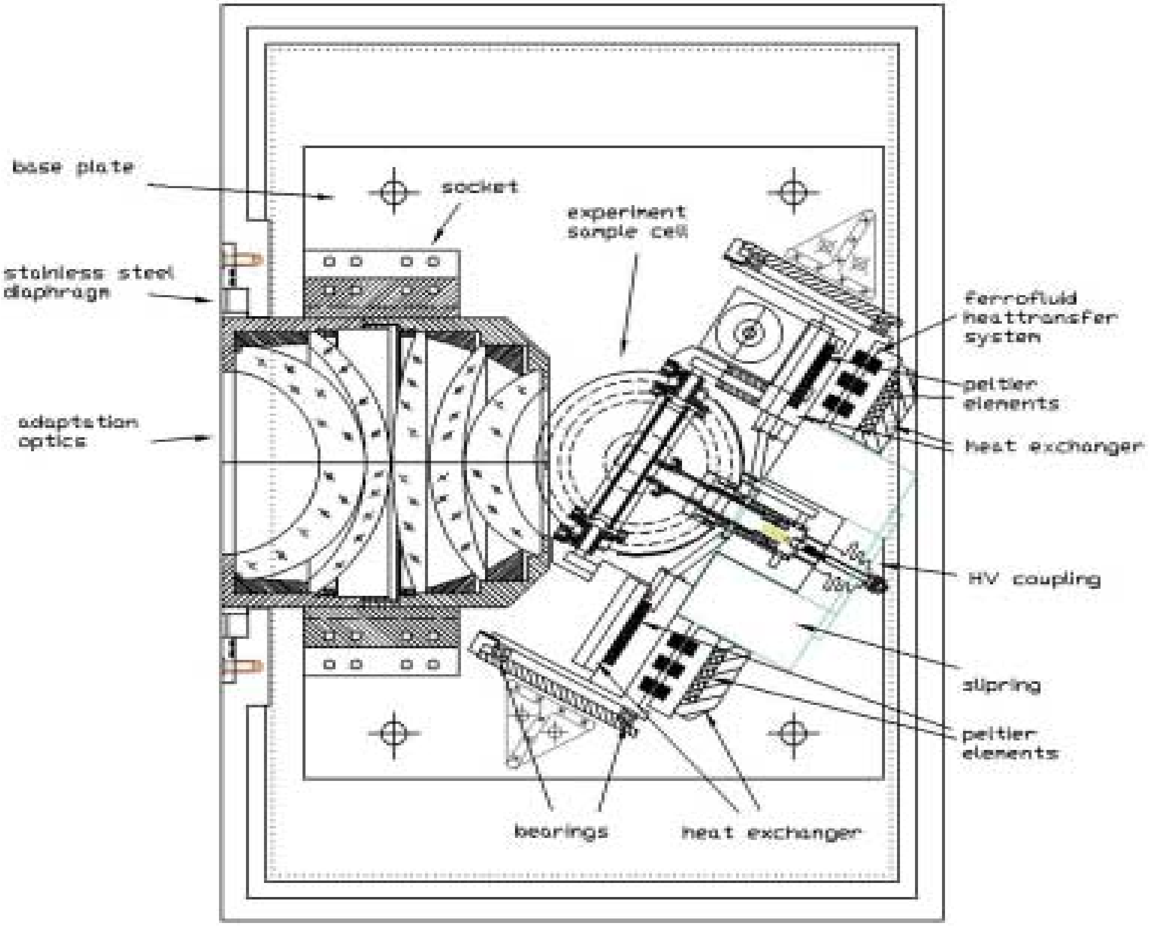

Dimensions of Experiment Container for ISS:
GEOFLOW: X: 400 x Y: 270 x Z: 280 mm

In: Ch. Egbers, W. Beyer, A. Bonhage, R. Hollerbach, and P. Beltrame. The GEOFLOW-Experiment on ISS (Part I): Experimental preparation and design. **Advances in Space Research**, 32(2): 171–180, 2003

GEOFLOW: Flight model testing

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GEOFLOW EC Flight Model Tests at EADS-Astrium; Friedrichshafen

Summary and Outlook (GEOFLOW)

GEOFLOW Simulation (parameter variations)

• Dynamics of supercritical flow (high Rayleigh-, Taylor-numbers)

• Nature of mode interactions / bifurcations with method of path following

• Transition to chaos

GEOFLOW Earth Lab (parameter variations)

• Commissioning: thermal tests, high voltage tests, rotational tests

• Experimental investigation and comparison with numerical simulation

• Evaluation of data interpretation method for Wollaston shearing interferometry (comparison of experimental and numerical data)

EC GEOFLOW Launch

• Preliminary manifest for increment 16 (Dec. 2007 - May 2008)

• GEOFLOW will fly up with STS-1E flight, fly back with STS-1J flight

• Reflight of GEOFLOW with LDV-technique (planned for 2009)

Central force field generation

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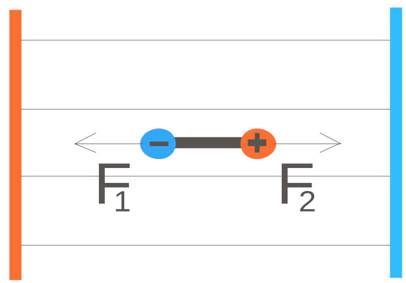
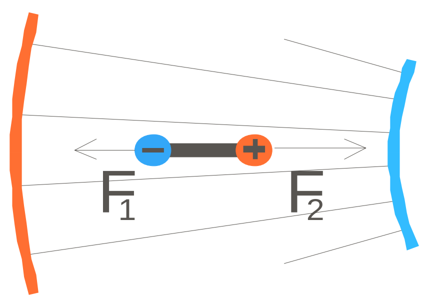
Homogenious field:

$F_1 = -F_2$, no force on dipole



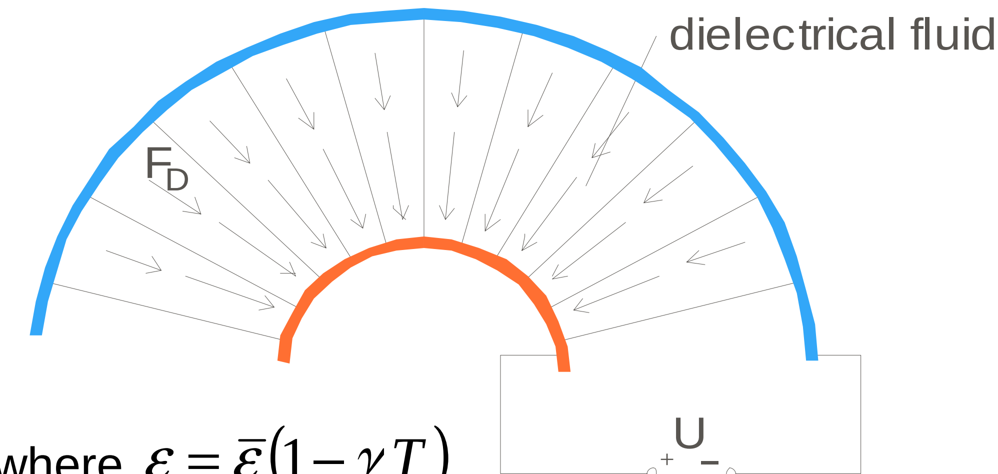
Inhomogenious field:

$F_1 < -F_2$, force on dipole towards stronger field region



The dielectrophoretic force acts on dielectric fluids:

$$\vec{F} \propto \varepsilon_r \vec{\nabla}\left(\vec{E} \cdot \vec{E}\right) \qquad \vec{F} = \vec{g}_E \rho \gamma T$$



where $\varepsilon = \bar{\varepsilon}\left(1 - \gamma T\right)$

Thus, for a spherical gap, an effective dielectrophoretic „gravity“ can be defined:

$$\vec{g}_E = \frac{2\bar{\varepsilon}}{\rho}\left(\frac{R_1 R_2}{R_2 - R_1} U_{rms}\right)^2 \frac{1}{r^5} \vec{e}_r$$