Anlage 1 | Attachment 1

to terms of conditions for access to the

DFG Core Facility Centre "Physics of Rotating Fluids"

1. Research facilities

The dynamics of rotating and/or stratified flows play a fundamental role in many technical and also geophysical applications (Hopfinger, 1992). E.g., they are of importance in liquid planet cores (Tilgner, 2009), but also in oceans and atmospheres. Moreover, in industrial rotating flows and spacecraft design (Agrawal, 1993) or in industrial mixing processes of stratified liquids they are of great relevance. From a fundamental point of view rotating and/or stratified fluids are different from classical homogeneous non-rotating flows by two central aspects. First, they support new classes of waves, internal waves, inertial waves, and, when rotation and stratification is present, inertial gravity waves (Pedlosky, 2003). Second, they show a very different behavior for large Reynolds numbers since turbulence is highly anisotropic. In the most extreme case, i.e. for strong stratification of fast rotation, the turbulence becomes 2D and energy is pumped upscale. Hence, small features 'feed' larger structures which is a rather counterintuitive process. These two central aspects of rotating and/or stratified flows are a major part of two current directions of research in fluid dynamics. One is the study of coherent structures in transitional and turbulent flows. Whenever a fluid supports waves it is likely that these waves can form structures even in fully turbulent flow (Nazarenko, 2011). However, major issues of the interaction of waves in turbulent flows are unknown or only poorly understood. The other direction is related to a theoretical description of flows with anisotropic turbulence (Davidson, 2013). Scaling laws for this kind of flows differ from the standard models and such laws need to be tested experimentally. It is obvious that such problems need to be attacked preferably by a broad community that has access to experiments and modern measurement equipment to analyze rotating and stratified flows. Considering the goal of establishing a new national and international core facility center for "Physics of Rotating Fluids (PRF)" we describe our preliminary work in this field and connect this to recent studies and the most relevant literature. Doing so it will become clear that the experiments and technical equipment available at the Fluid-Center at BTU (CE) are very well suited to address the problems mentioned above and form an ideal basis for such center of "Physics of Rotating Fluids (PRF)".

1.1. The spherical gap flow apparatus (DFG EG 100/1-1, 1-2)

The spherical gap flow apparatus (Fig. 1) was already built up in 1996 for investigations of laminar-turbulent transition phenomena in isothermal flows (Egbers & Rath, 1995, Liu et al., 1996; Wulf et al., 1999). Later on, this experiment was used to detect Stewartson-layers in differentially rotating spheres (Hollerbach et al., 2004). In parallel we did numerical simulations and could reproduce the spiral wave flow in a very good agreement (Hollerbach et al., 2006). Since 2002 this experiment was also used as a laboratory breadboard for the GEOFLOW-experiment series of thermal convection with axial (Travnikov et al., 2002; Futterer et al. 2007; Scurtu et al., 2010) or radial temperature gradient and dielectrophoretic force field on ISS described in Sitte et al. (2001), Egbers et al. (2003).

Actually, this experiment is used to investigate inertial waves and in particular different forcing mechanisms to excite inertial wave modes. On the one hand the modes can be excited by modulating the shell's rotation (Koch et al., 2013), on the other hand the modes can be excited via shear instability due to differential rotation of the inner and outer sphere (Rieutord et al., 2012). Inertial waves and wave modes are believed to contribute strongly to the transport of mass and energy in geophysical and astrophysical flows in planetary cores, accretion disks and dynamos in precession. Presently, the issue of mode excitation (Aldridge and Toomre, 1969) is controversially discussed (Zhang et al., 2013). However, it is necessary to clarify this since such modes are involved in the generation of mean flows, and support fluxes induced by turbulent fluctuations. Waves and instabilities play a role in the thermohaline circulation of the oceans (Maas and Harlander, 2007), local wave generation (Harlander and Maas, 2006, 2007a, b), and in the variations of the zonal winds in the equatorial atmosphere (Plumb, 1977). It has been shown in previous studies that a direct resonant forcing of inertial waves can lead to the generation of a strong zonal wind (Tilgner, 2007). This is most relevant in the astrophysical context, because the flow properties in the liquid cores of celestial bodies are known to be strongly affected by harmonic libration, precession or nutation. A set of complementary experiments are currently under development at BTU together with IRPHE, Marseille and FAST, Paris. It is surprising how well inertial wave modes can be excited by differential rotation. It appears that this forcing is more efficient than libration.

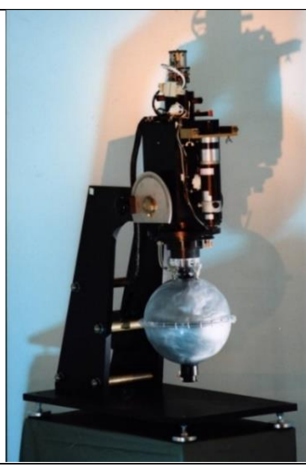
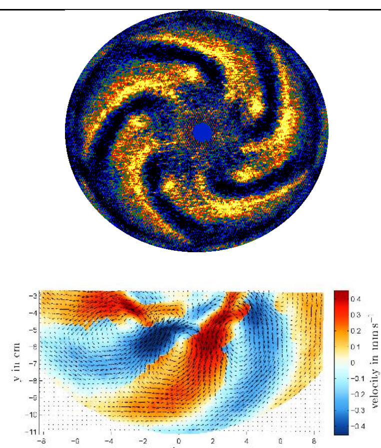
		**Control parameters:** Reynolds number: $Re_{i,o} = (R_{i,o}\, d\, \Omega_{i,o})/\nu$ Rayleigh number: $\mathrm{Ra} = \frac{\alpha g_E \Delta T}{\nu \kappa} d^3$ Prandtl number: $Pr = \nu/\kappa$ radius ratio: $\eta = R / R$
(a) Spherical gap experiment	**(b): Flow visualization study (top), PIV measurement (bottom)**	**(c): Dimensionless Parameters**

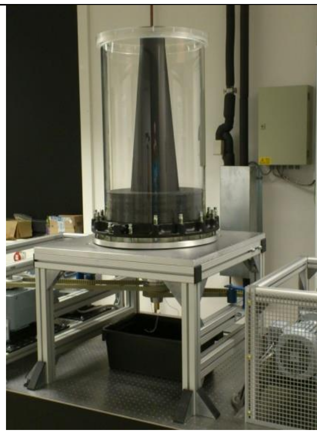
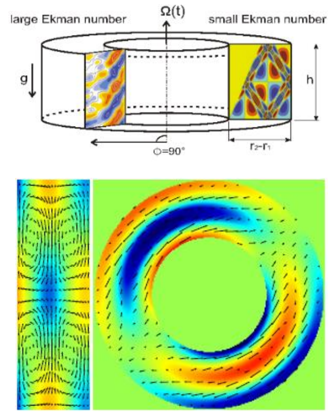
Figure 1: The spherical gap experiment

However, in contrast to libration, a variety of waves is excited due to the shear instability. Recent experimental results with the BTU spherical shell show that spiral-like inertial wave modes propagate in the bulk of the shell whereas trapped Rossby waves exist in the Stewartson layer.

This nicely confirms numerical results by Schaeffer and Cardin (2005). There are also first signs of wave triads that signal transition to turbulence. Inertial wave turbulence in spherical shells is not well understood. In a recent paper Sauret et al. (2013) discuss the interaction between turbulence and inertial waves. It appears that only waves with a certain frequency are emitted from the turbulent flow. The process of frequency selection remains puzzling but connects nicely with meteorological observations showing that the emission of internal gravity waves from the turbulent atmospheric boundary layer is frequency selective (Dohan and Sutherland, 2005).

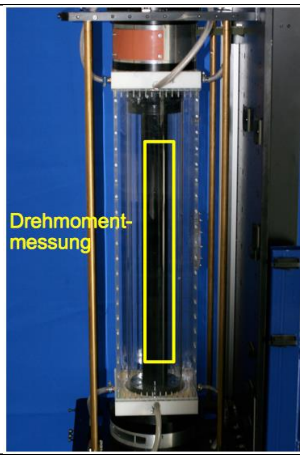
1.2. Quasi-Biennial Oscillation (QBO) experiment (DFG EG 100/14-1; HA2932/6-1)

The Quasi-Biennial Oscillation (QBO-) experiment (Fig. 2) is an example of successful co-operation inside the CFTM[2]: BTU studied inertial wave excitation and wave attractors in an annulus with an inner frustum in the laboratory (CE, UH) and direct numerical simulations (DNS) supervised by Eberhard Schaller and Andreas Will (Meteorology). This study is thematically connected to the work described for the spherical shell. However, the annulus geometry is simpler and due to the larger size of the tank smaller Ekman numbers can be reached. This allows for experiments similar to the one done by Plumb and McEwan (1978) to explain how gravity waves can drive the QBO, an oscillating mean flow in the equatorial stratosphere. In the BTU experiment inertial waves play the role of gravity waves. The question was whether inertial wave driven mean flows resemble internal wave driven flows. As for the spherical shell geometry, inertial waves were excited due to liberation of the inner or outer part of the annulus. This is in a sense similar to the configuration of McEwan (1970). The advantage of our setup is that inertial waves are excited at predefined regions that depend on the boundaries that oscillate. This allows the different wave excitation mechanisms to be separated. Inertial waves are efficiently excited when fluid particles are forced to cross surfaces of constant angular momentum (in analogy to gravity waves that can be excited by pushing fluid particles across surfaces of constant density). It turned out that boundary layers play a much more important role for the mean flow generation in the liberating tank compared to the experiments by Plumb and McEwan (1978) and the mean flow structures differ significantly. However, due to our setup we were able to separate the effects of the different boundary layers. Usually, in studies with an entire tank librating, the Stokes and Stewartson layers at the vertical walls are neglected or treated schematically (Wang 1970; Busse 2011). In contrast, we could very clearly distinguish between the Stokes/Stewartson layer effects and the effects from the Ekman layers. We further study efficiency of wave excitation and how the latter depends on frequency. We found that wave excitation is most efficient for frequencies for which the boundary layers erupt. These frequencies are different for the different boundary layers that are involved in the libration process. Our findings are summarized in a series of papers (Borcia & Harlander, 2013; Borcia et al., 2014; Klein et al. 2014). As was mentioned for the spherical shell, inertial wave turbulence is not well understood. This is due to the strong anisotropy of turbulence in rotating flows and due to nonlinear wave interactions and wave selection processes that are still unclear. The QBO-Taylor-Couette system is ideally suited to investigate wave turbulence in rotating flows: it allows for small Ekman numbers due to fast rotation and a wide gap, it allows for a controlled wave excitation (either by libration or by differential rotation), and it is accessible to optical measurement techniques from top and side view.

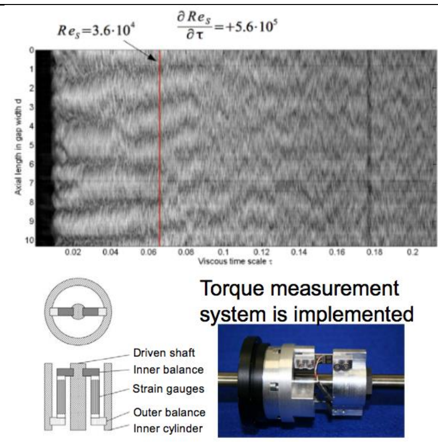
		**Control parameters:** Ekman number: $Ek = \nu/(\Omega_0 d_o^2)$ Rossby number: $Ro = U/(\Omega_0 d_o)$ Modulation frequency □(t) = □$_0$ (1 + □ sin[□t]) radius ratio: $\eta = R_i / R_o$ rotation ratio: $\mu = \Omega_o / \Omega_i$
(a): Rotating annulus experiment (QBO)	**(b) Principle sketch of wave attractors and wave modes**	**(c): Dimensionless numbers**
Figure 2: The rotating annulus (QBO)-experiment		

1.3. **The Taylor-Couette apparatus** (DFG EG 100/2, EG 100/7; EG 100/15-1, 15-2; FOR1182)

Different Taylor-Couette experiments have been headed by CE since the late 1990´s. The first apparatus (EG 100/2) was used to investigate the influence of asymmetric boundary conditions on the dynamics of Taylor-Couette flow where the inner cylinder and the bottom plate co-rotated, while the outer one was at rest like in a rotor-stator-cavity flow (Meincke et al., 2000). The second apparatus (EG 100/7) was built-up to investigate the dynamics of fluid flow with superposition of rotation and a radial temperature gradient between inner and outer cylinders (Deters et al., 2008). The third one as illustrated in Fig. 3 is actually used for investigations of fully developed turbulent Taylor-Couette flows in wide gap configurations (Merbold et al., 2011). This work is part of the running DFG research group “Turbulence”, FOR 1182, headed by CE (EG 100/15-1, 15-2, EG100/16-1, 16-2). There are two central and unresolved questions in astrophysics that are related to Taylor-Couette flows. The first one is how to get the Keplerian flow profile unstable (Shalybkov and Rüdiger, 2005). The Keplerian profile is a model for the flow in an accretion disk and this profile is ‘shallower’ than Rayleigh-unstable flows, hence the Keplerian profile is linearly stable. One possibility to enhance instability is to add a magnetic field and triggering the so called Magneto-Rotational Instability (MRI). Future studies in co-operation with Innocent Mutabazi (LOMC, Le Havre) are devoted to the MRI which is believed to play a crucial role in planetary dynamos and accretion disks, its experimental demonstration requires challenging conditions. In the limit of large magnetic Reynolds number (Rm >> 1), the MRI equations have a strong analogy with the equations governing viscoelastic instabilities, as described by the Oldroyd-B model in the limit of large Weissenberg number (Wi >> 1) (Ogilvie and Proctor, 2003). Our aim is to conduct joint experimental and numerical studies of viscoelastic Couette-Taylor flow in the appropriate parameter range for the MRI analogy. Another option to make the Keplerian profile unstable is to add a stable stratification (Withjack and Chen, 1974).This is the so called Stratorotational Instability (SRI) that will be discussed later. The second central question related to Taylor-Couette flows is how efficient angular momentum is transported outward when the flow *is* turbulent. Related to this is the question on how the turbulent angular momentum transport scales with the input parameters, e.g. the Reynolds number and the rotation ratio (Eckhardt et al., 2007). The transport shows a distinct maximum for a certain rotation ratio (van Gils et al., 2012; Paoletti and Lathrop, 2011; Merbold et al., 2013) but the reason for this maximum is still under debate. Presently, the flow structures around the torque maximum are investigated (Brauckmann & Eckhardt, 2013) and ‘bursting’ events seem to play a relevant role. In this context we also should mention an interesting discovery made in the high Reynolds number regime. Looking for the ultimate turbulent regime in the Taylor-Couette flow, Huisman et al. (2014) surprisingly found multiple turbulent states. This implies states of different angular momentum transport even in fully turbulent flow.



(a): Taylor-Couette experiment



(b) Flow visualization and space-time-plot (top); Torque measurement system integrated into the inner cylinder (bottom)

Control parameters:

Reynolds number: $Re_{i,o} = (R_{i,o}\ d\ \Omega_{i,o})/\nu$

aspect-ratio: $\Gamma = H/d$

radius ratio: $\eta = R_i / R_o$

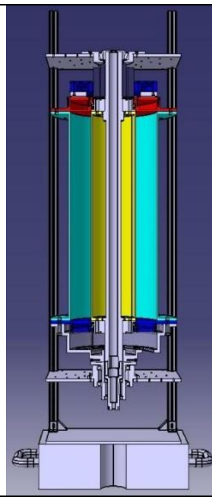
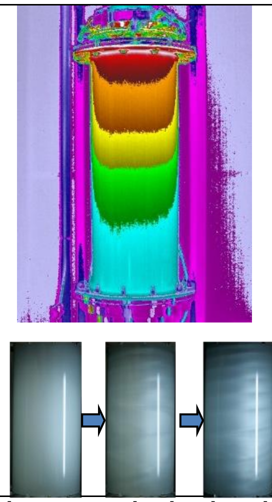
rotation ratio: $\mu = \Omega_o / \Omega_i$

(c): Dimensionless parameters

Figure 3: The Taylor-Couette experiment

1.4. Strato-Rotational-Instability (SRI) experiment (DFG EG 100/18-1; HA2932/7-1)

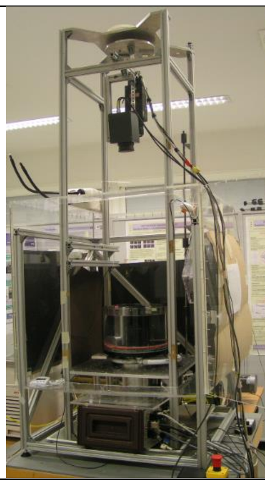
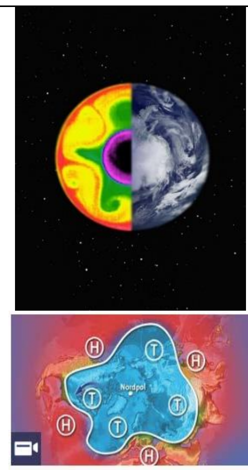
We have mentioned in the Taylor-Couette part above that one option to get Keplerian flows unstable is to introduce stratification. Such an instability is necessary to explain the open astrophysical problem on how material from an extended (protoplanetary) accretion disk can reach the center and form a slow rotating solid central body (Shalybkov and Rüdiger, 2005; Gellert and Rüdiger, 2009). Conservation of angular momentum prevents this collapse. Some source of greatly enhanced dissipation is necessary and very likely this source is related to turbulence. Purely hydrodynamic disks are stable (Ji et al., 2006), hence some other mechanisms are required to destabilize the disk.

		**Control parameters:** Reynolds number $Re=\Omega_i R_i D/\nu$ Froude number: $Fr = \Omega_i / N$ Buoyancy frequency: $N^2=-(g/\rho_0)\, d\rho /dz$ radius ratio: $\eta = R_i / R_o$ rotation ratio: $\mu = \Omega_o / \Omega_i$
(a) Sketch of SRI-experiment	**(b): Thermography (top) and flow visualization (bottom)**	**(c): Dimensionless parameters**
Figure 4: The Strato-Rotational (SRI-)experiment		

At BTU, we investigate the strato-rotational instability (SRI) that appears in a stratified disk. Initial experiments as illustrated in Fig. 4 have shown that the instability exists in the laboratory and results agree with linear stability analysis (Le Bars and Le Gal, 2007). However, comparison with accompanying nonlinear simulations could lead to a deeper understanding of the instability mechanism and its relevance for astrophysical applications. Secondary bifurcations further away from the marginal stability line have not yet been investigated and are feasible with the new experimental set-up as well as with numerical simulations. Moreover, it is important to clarify the relation between SRI and so called radiative instabilities (Le Dizes and Riedinger, 2010; Park and Billant, 2013). The latter explains the growth of perturbations due to inertia-gravity waves that are reflected between the disk's center and a critical level. The so called overreflection at the critical level then leads to a growth in wave amplitude and finally to turbulence due to wave breaking. Radiative instability might not be alone a factor in the formation of planetesimals in accretion disks, but also in the radiation of energy from the convective zones of stars towards their radiative zones. Also in the context of stratified vortices in oceans and the atmosphere SRI and radiative instabilities are of large interest (Park and Billant, 2012) which underpins the necessity to conduct experiments with the stratified Taylor-Couette apparatus.

1.5. **The baroclinic wave tank experiment** (DFG EG 100/3; EG 100/13-1, 13-2, 13-3; SPP 1276 “MetStröm”)

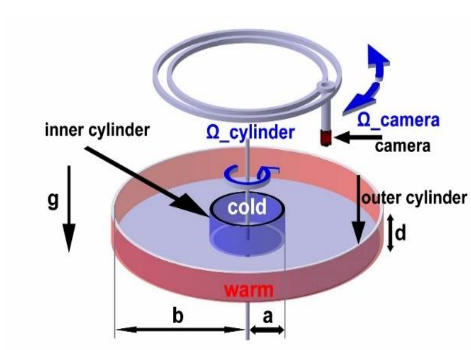
In 2000 BTU (CE) started his first baroclinic wave tank experiment to investigate the transition phenomena to irregular flows (Sitte & Egbers, 1999(a); Sitte & Egbers, 1999(b); Sitte & Egbers, 2000; von Larcher & Egbers, 2005). Later on, this experiment became a reference experiment (Fig. 5) inside the German-wide DFG priority program “MetStröm”. Baroclinic waves are responsible for the transport of momentum and heat in atmospheres and oceans. The differentially heated rotating annulus is a widely studied laboratory model describing the main aspects of cyclogenesis and the general mid-latitude atmospheric circulation. The radial temperature difference in the cylindrical tank and its rotation rate can be set such that the isothermal surfaces in the bulk become tilted with respect to the direction of gravity, leading to the formation of baroclinic waves. The signatures of these waves at the free water surface have been analyzed via infrared thermography in a wide range of rotation rates (keeping the radial temperature difference constant) and under different initial conditions. In parallel to the laboratory experiments, five groups of the MetStröm collaboration have conducted numerical simulations using the experiment's geometry and the experimental parameters. They used different approaches and solvers, and applied different initial conditions and perturbations. The experimentally and numerically obtained results have been evaluated and compared in terms of their dominant wave modes, spatio-temporal variance properties and drift rates. Thus certain "benchmarks" have been created that can later be used as test cases for atmospheric numerical model validation (Borchert et al., 2014; Vincze et al., 2014; Hoff et al., 2014).

		**Control parameters:** Taylor number: $Ta = \frac{4 \cdot \Omega^2 \cdot (b-a)^5}{\nu^2 \cdot d} = f(\Omega)$ Rossby number: $Ro = \frac{g \cdot d \cdot \alpha \cdot \Delta T}{\Omega^2 \cdot (b-a)^2} = f(\Delta T, \Omega)$ Aspect ratio: $\Gamma = (b-a)/d$ Radius ratio: $\eta = a / b$
(a): Baroclinic wave tank	**(b): Flow visualization and observation from satellite (top); Stable baroclinic wave (source: ARD Jan. 2014, bottom)**	**(c): Dimensionless parameters**
Figure 5: The baroclinic wave tank experiment		

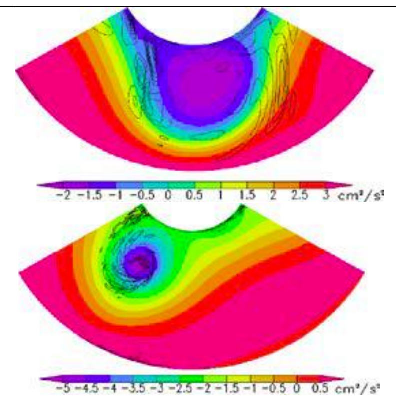
The MetStröm priority program focused on multiple-scale processes. In recent years the interest on small-scale waves that are related to baroclinic fronts has strongly increased since the small features have to be parameterized in numerical weather models (see the MS-Gwaves project). In two MetStröm spin-off projects conducted with A. Randriamampianina and P. Le Gal from Marseille and Th. v. Larcher from FU Berlin (DAAD-PROCOPE program 'baroclinic waves, ref. 55908227; EuHIT-BaroStrat) we studied the occurrence of internal gravity waves in the baroclinic annulus. The DAAD-PROCOPE project was intended on gravity waves that result from boundary layer instability (Randriamampianina, 2013). In the EuHIT-BaroStrat project we tried to produce a thin baroclinically unstable layer in a salt stratified fluid. The question is, whether from this layer gravity waves can be emitted into the stable regions of the flow. This is part of an important new research direction in fluid mechanics: the generation of waves from turbulence (Dohan & Sutherland, 2005; Sauret et al., 2013). Since many years, the generation of turbulence from waves have been studied, but it appears that the reverse process is as important since local turbulence that generates waves can lead to remote changes of energy and momentum. This is of great relevance for technical and environmental applications.

1.6. **The MS-GWaves experiment** (HA2932/8-1; FOR 1898)

As mentioned above, the MetStröm priority program was intended to study the coexistence of large and small scale waves. The interest on small-scale waves that are related to baroclinic fronts has strongly increased since it is urgent to parameterize this particular wave source for numerical weather models (Borchert, Achatz and Fruman, 2014). BTU (UH) contributes to this topic within a new interdisciplinary DFG research group (FOR1898) with a new reference experiment on MS-Gwaves (Fig. 6): A differentially heated rotating annulus experiment, similar to the baroclinic wave tank but larger, is currently built up. It provides the necessary reference data for benchmarks of model simulations at Goethe University of Frankfurt (U.Achatz) and Leibniz-Institute of Atmospheric Physics (IAP), Kühlungsborn (Ch. Zülicke). The size of the tank accommodates the fact that the buoyancy frequency N in the atmosphere is much larger than the Coriolis parameter f.



(a): Sketch of MS-GWaves experiment



(b): Pressure fields and contour lines of the horizontal velocity divergence: Experiment (top) and atmosphere-like configuration (bottom)

Control parameters:

Taylor number:

$$Ta = \frac{4 \cdot \Omega^2 \cdot (b-a)^5}{\nu^2 \cdot d} = f(\Omega)$$

Rossby number:

$$Ro = \frac{g \cdot d \cdot \alpha \cdot \Delta T}{\Omega^2 \cdot (b-a)^2} = f(\Delta T, \Omega$$

Aspect-ratio:

Γ= (b-a)/d

radius ratio:

η = a / b

(c): Dimensionless parameters

Figure 6: The MS-GWaves experiment

Statistical tests developed at Universita della Svizzera Italiana (USI), Lugano, Switzerland (I. Horenko) will be used to optimally detect possible shortcomings in the proposed parameterizations in dependence of crucial flow parameters, such as rotation rate and radial temperature difference (Horenko et al., 2011). It is important to carry out further purpose-oriented experiments. The new large baroclinic tank allows further to do experiments on realistic wave-topography interactions (Read and Risch, 2011) with small Ekman numbers and a more realistic N/f, two claims that cannot be fulfilled by the classical baroclinic tank setup used in MetStröm or in other laboratories.

1.7. The Geoflow experiments (DLR, ESA)

BTU (CE as principle investigator, PI) carried out experiments together with European scientists in spherical shell geometry on electro-hydrodynamic driven Rayleigh–Bénard convection. These experiments have been performed for both temperature independent (‘GeoFlow I’) and temperature-dependent fluid viscosity properties (‘GeoFlow II’) like in the Earth´s interior (Davaille & Jaupart, 1994; Androvandi et al. 2011). To set up a self-gravitating force field, a high-voltage potential between the inner and outer boundaries and a dielectric insulating liquid is used (Yavorskaya et al. 1984; Hart et al. 1986; Bercovici et al, 1989(b)); the experiments (Fig. 7) were performed under microgravity conditions on the International Space Station in the Fluid Science Laboratory (Egbers et al., 2003). In front of these experiments we did stability analysis (Travnikov et al., 2003), numerical simulations (Beltrame et al., 2006) and bifurcation analysis (Beltrame et al., 2003) in three-dimensional spherical geometry to reproduce the results expected in the ‘GeoFlow’ experiments. We used Wollaston prism shearing interferometry for flow visualization – an optical method producing fringe pattern images. In ‘GeoFlow I’, we saw a sheet-like thermal flow. In this case convection patterns have been successfully reproduced by three-dimensional numerical simulations using two different and independently developed codes (Futterer et al., 2011, Feudel et al., 2011). In contrast, in ‘GeoFlow II’, we obtain plume-like structures (Futterer et al., 2013; Futterer & Egbers, 2014) in a very good agreement with previous work of Christensen & Harder (1991).

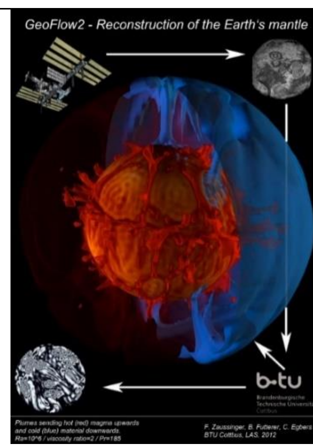
		**Control parameters:** Taylor number: $Ta = \frac{4 \cdot \Omega^2 \cdot (b-a)^5}{\nu^2 \cdot d} = f(\Omega)$ Rayleigh number: $\mathrm{Ra} = \frac{\alpha g_E \Delta T}{\nu \kappa} d^3$ with: $\vec{g}_{central} = \frac{2\bar{\varepsilon}}{\rho} \left(\frac{R_1 R_2}{R_2 - R_1} U_{rms} \right)^2 \frac{1}{r^5} \vec{e}_r$ Prandtl number: Pr = ν/κ radius ratio: η = a / b
(a): The Geoflow experiment container (integrated in the Fluid Science Laboratory of COLUMBUS module)	**(b): Reconstruction of the fluid flow in the Earth´s interior due to GEOFLOW experiment in spherical shells**	**(c): Dimensionless parameters**

Figure 7: The GEOFLOW experiment on International Space Station (ISS)

1.8. Summary

We think that the experiments and instruments described above and provided to the community of fluid dynamics, geo-/astrophysics, meteorology, oceanography, and engineering in form of a core facility center for “Physics of Rotating Fluids (PRF)” helps to bring the discipline of rotating/stratified flows forward. The questions addressed strongly prompt a common effort. Moreover, a cross-fertilization between researches from different research units will have a strong synergy effect necessary to entangle the complex issues that have been addressed above and are inherent to turbulent rotating and stratified flows. In Table 1, we summarize the non-dimensional parameters and parameter ranges of the experiments (for definition of the parameters see boxes in Figs. 1-7).

Exp.	η radius ratio	Γ aspect ratio	Ω_{max} **[rpm]**	**Re**	**Ek**	**Ta**	**Ra**	**Pr**	**Fr**	**Ro**
Sphere	0.36-0.5		200	10^4-2 10^5			10^5-10^7			
QBO	0.25-0.5	4	150		10^{-4}-5 10^{-6}					10^{-1}-10
TC1 TC2	0.1-0.71 0.5	20-35 20	150 480	0 -2 10^5 0 -10^6						
SRI	0.5	10	60	2 10^2-4 10^4				7-60	1-620	
Baro. wave	0.3-0.5	4	40			10^5-10^8		7		10^{-1}-10
MS-Gwaves	0.28	10	30			10^5-10^9		7		10^{-2}-10
Geoflow	0.5		12			10^4-10^7	10^6	10^1-10^2		

Table 1: The non-dimensional parameters of the experiments (definition of the parameter see boxes in Fig. 1 to 7)

2. References

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