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# LABORATORY AND THEORETICAL MODELS OF

# PLANETARY-SCALE INSTABILITIES AND WAVES

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Meteorologists and astrophysicists interested in global planetary and solar circulations have long recognized the importance of rotation and stratification in constraining the character of these flows. In particular, the effect of latitude-dependent Coriolis forces, the so-called beta-effect, is thought to play a crucial role in such phenomena as differential rotation on the Sun, cloud band orientation on Jupiter, and the generation of magnetic fields in thermally driven dynamos. Most theoretical works, and all prior laboratory studies on these problems, have treated the curvature effects only locally, and the laboratory efforts have only been able to consistently study beta-effects in layered quasi-geostrophic models.

The continuous low-g environment of the orbiting space shuttle provided a unique setting for conducting geophysical fluid model experiments with a completely consistent representation of sphericity and the resultant radial gravity found on astrogeophysical objects. This is possible because in zero gravity one can construct an experiment that has its own radial buoyancy forces. The dielectric forces in a liquid, which are linearly dependent on fluid temperature, give rise to an effectively radial buoyancy force when a radial electrostatic field is applied. The Geophysical Fluid Flow Cell (GFFC) experiment is an implementation of this idea in which fluid is contained between two rotating hemispheres that are differentially heated and stressed with a large a-c voltage. The GFFC flew on Spacelab III in May, 1985. Data in the form of global Schlieren images of convective patterns were obtained for a large variety of configurations. These included situations of rapid rotation (large Taylor numbers), low rotation, large and small thermal forcing (ie. a range of Rayleigh numbers based on the electrostatic gravity and the statically unstable radial temperature contrast), and situations with applied meridional temperature gradients. Our group has been involved with the analysis and interpretation of the GFFC-85 data. We have also developed improvements to the GFFC instrument that will allow for real-time (TV) display of convection data and for near-real-time interactive experiments. These experiments, on the transition to global turbulence, the breakdown of rapidly rotating convective planforms (banana cells) and other phenomena, are scheduled to be carried out on the International Microgravity Laboratory (IML-1) aboard the shuttle in June, 1990.

**Research Accomplishments over the period June 1987 - June 1988**

Planform Selection

The plane parallel model of nonlinear planform selection was extended to spherical geometry. In planar geometry, the (GFFC) observed tendency for down-center hexagons at low Taylor number was generated by the fact that the inner GFFC spherical surface has stronger gravity. In spherical geometry, a similar effect is present. However, numerical simulations (using Glatzmaier's model) have indicated a preference for down-center hexagons even with inverse r-squared gravity, with a small enhancement for inverse r-fifth gravity. The weakly nonlinear model does not have this property, suggesting that the GFFC experiments may have been influenced by more than one desymmetrizing force. Future GFFC experiments, looking again at a range of low Taylor numbers with better thermal boundary control than on SL-3 shall re-address this planform selection issue.

## Spiral Waves

The rather astounding superposition of spiral waves alongside strong north-south columnar convective rolls at moderate Taylor number was addressed by studying the linear stability properties of local Hadley circulations (Hart, 1988). The locally planar, exact, Hadley circulation changes with latitude. At the poles the zonal flow is strong, whereas at the equator it is very weak (with the bulk of the basic state flow being tied up in a simple meridional circulation). Linear eigenfunctions tended to line up with the ambient shear (for the moderate Prandtl number of the GFFC experiment). As one approaches the pole, the linear modes are locally at an angle of up to 45 degrees with respect to a meridian. Whereas near the equator, the axes of the most unstable modes are within 10 degrees of a meridian. This tendency may explain the different characteristics of the polar and equatorial modes observed in the SL-III GFFC data.

## Columnar Convection

We have studied the GFFC flight data in detail in order to understand the competition between columnar cells (banana cells) at lower latitudes and strong disturbances at higher latitudes (e.g. Toomre, Hart, and Glatzmaier 1987). Under the most nonlinear conditions considered with GFFC, we find that there remain distinct signatures of banana cells at low latitudes, and this suggests that similar giant convection cells may indeed be present deep within the solar convection zone. The GFFC data provides the only experimental means to directly study such rotationally-constrained convection, and thus our data is of great interest to the observational and theoretical efforts in helioseismology which will use the oscillations of the Sun to probe the interior dynamics of this star (Toomre, 1986, Hill et al. 1988). We are providing our GFFC imaging data on the banana cells, along with velocity and thermal fields from our three-dimensional simulations of these GFFC experiments, to the helioseismology working groups dealing with both the ground-based GONG project and the now-approved NASA/ESA SOHO spacecraft solar oscillations imager experiment. Our simulation data will permit frequency splittings to be calculated for potential oscillation modes to be used to search for the flows of the giant cells.

## Numerical Simulations

We have continued our major efforts in the numerical modelling of fully compressible convection, for it is essential to understand the effects of stratification on flows that can readily span multiple density scale heights in the vertical (Hurlburt, Toomre & Massaguer, 1986, 1988a, 1988b). Such work is vital in making the link between results from our GFFC experiment and real convective flows in the Sun or in the giant planets. We have recently begun the first substantial three-dimensional simulations of compressible convection (employing 64x64x64 modes) with Dr. Fausto Catteneo, and we find that the pronounced asymmetries between strong, concentrated downflows and weaker, broader upflows seen in our 2-D simulations are retained. However, the sheets of downflow at cell peripheries, evident near the top of the layer, turn into distinct plumes at greater depths, and thus the topology of the cells changes noticeably with depth. The compressible code has been further used to investigate convection in the presence of strong magnetic fields, and of buoyancy instabilities of intense fields, as might be occurring near the base of the solar convection zone (e.g. Cattaneo & Hughes 1987, 1988, Hughes, 1987, Hughes and Cattaneo, 1987, Cattaneo, 1988). We have also studied the properties of travelling and modulated waves in convection, dealing with doubly diffusive convection with its remarkably rich bifurcation structure (Deane, Knobloch & Toomre, 1987, 1988). This latter problem is analogous to that for rotating polar convection, and solutions found will be useful in interpreting GFFC data.

## Experiment Modifications

A design for converting the GFFC film camera into a combined 16mm film and real-time TV downlink camera has been developed following the ideas of the PI (J.E. Hart). The PDR for the Univ. of Colo. Video Acquisition Module was held in April, and the Critical Design Review is scheduled for Aug. 9. All circuits have been breadboarded and successfully tested. An approved parts list has been generated. Delivery and integration of the Video Module is scheduled for Fall, 1988.

## Research Plans

### Theoretical Modelling

Instability calculations using the exact parallel flow Hadley circulations as basic states will be continued. Prandtl numbers other than the previous GFFC flight value will be considered. The results will be compared to numerical calculations using a full (nonlinear) axisymmetric state by Miller et. al. at UAH.

### Data Analyses

Using much higher resolution TV-imaging technology, with the capability of extensive noise reduction (through real-time averaging and smoothing), the Spacelab-III data films will be redigitized. This time we intend to use the original films rather than copies, in order to capture subtle details and to expand the dynamic range of the secondary data products such as the longitudinal wavenumber spectra. The data films will be archived in digital form on read-only laser discs. These data will be used to analyze the

Rayleigh number evolution of spiral and cross waves in situations with moderate to strong north-south heating.

## Numerical Simulations

We are planning to undertake a major new series of direct three-dimensional simulations of GFFC convection, and use these to help guide the experimental parameter values to be employed during the IML-1 reflight of GFFC. We will be using a refined version of the pseudo-spectral code devised by Dr. Gary Glatzmaier, employing spherical harmonics in the horizontal and Chebyshev polynomials in the radial direction. Dr. Nicholas Brummell from Imperial College, London will be joining us as a postdoc to participate in these simulations, and we expect to carry out much of the work on the NASA-Ames NAS Cray-2 supercomputers. Those machines with their 256MWord memories are essential if we are to use the 4000 or more spherical harmonics in the nonlinear simulations, and such modal resolution is required to begin to make contact with the parameter values that we can readily attain with the GFFC. These Cray-2 machines are accessible by fast network links form Boulder, and we now have available Unix-based IDL software for interactive analysis and display of the planned simulations. Such modelling is not only very demanding of computing resources, but the data sets to be produced are massive and the techniques for visualizing the flows are challenging. We have developed considerable experience with many aspects of these challenges through our current three-dimensional compressible simulations, and thus we are confident that together with Drs. Cattaneo and Glatzmaier we can learn a great deal from these new simulations of GFFC flows.

## Experiment Integration

The real-time television module shall be installed into the current GFFC instrument. The system shall be calibrated (optically) and tested as a functional unit, complete with the interactive display and experiment control software that shall enable the astronaut to change experiment parameters in response to particularly interesting convection data.

## Planning for IML-1

The GFFC real-time software shall be updated to include a set of experiment scenarios selected on the the basis of extensive numerical integrations and analyses of the previous flight data. The IML-1 flight runs will concentrate on the breakup of banana cells, the transition to unsteady (turbulent) convection, especially in situations (ie heating distributions) not investigated during SL-III. A backup set of executable scenarios will be set in GFFC ROM's for use in case there is a breakdown of the GFFC-GRID computer datalink. The Univ. of Colorado team will also be involved in astronaut science training, and in extensive preparations for launch and mission operations support. These activities will be coordinated by the PI's and Mr. Scott Kittelman who will re-join the project in September and who shall be in charge of ground support equipment and data analysis.

# List of Publications

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