youngest Beacon rocks present, which are most likely of early Late Triassic age. Jurassic time in this part of East Antarctica was one of intense volcanism, not glaciation.

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Buoyancy and Solar Spin-Down

Abstract. *The transition of a cylinder of water with a vertical density gradient between convective and viscous spin-down occurs near the point at which the maximum buoyancy force equals the radial pressure gradient that is driving the convection. A similar analysis applied to the sun shows the maximum buoyancy force to be 1500 times the convective force. A rapidly rotating solar interior would not be damped by large-scale convection.*

The rapidly rotating solar interior proposed as the cause of the oblateness observed by Dicke and Goldenburg (*1*) has been criticized by Howard *et al.* (*2*) on the ground that such a distribution of solar angular momentum would be unstable with respect to large-scale convection. This convection, driven by pressure gradients along the boundary of the rotating region, would quickly damp out any rotation of the interior relative to the surface. McDonald and Dicke (*3*) have countered this objection by pointing out that a density gradient in the direction of the gravitational field will produce buoyancy forces that tend to stop convection. In a laboratory experiment in which an axially rotating cylinder of water was slowed down (*3*), they have demonstrated that such a density-stratified fluid requires a much longer spin-down time. Their result indicates that convection can be prevented by a density gradient. Dicke (*4*) also demonstrated that solutions to mathematical models not involving convection do exist and that a uniformly rotating core with a differentially rotating shell is such a solution.

We have repeated the experiment of McDonald and Dicke and have confirmed their results. We varied the height of the liquid in the cylinder to determine the transition between the convective spin-down which occurs for uniform fluids and the viscous spin-down which occurs for density-stratified fluids. (By convective spin-down we refer to the meridional circulation of the fluid which results in rapid damping of the azimuthal circulation due to bulk transfer of angular momentum. The viscous spin-down process consists of purely azimuthal flow which is damped by the internal friction of the fluid.) The transition occurs near the point at which the buoyancy force F_B, calculated by integrating the difference between the local density ρ and the maximum density ρ_0 from the top to the bottom of the liquid, is equal to the convective force F_C. The convective force is obtained by integrating the pressure gradient along the radius of the cylinder.

$$F_B = \int_H^0 (\rho - \rho_0)\, g\, dz \qquad (1)$$

where g is the acceleration of gravity;

$$\rho = \rho_0 - [(\rho_0 - \rho_{H_2O})/H]z \qquad (2)$$

ρ_{H_2O} is the initial density at the top of the cylinder, taken to be that of distilled water; H is the height of the cylinder of fluid; and z is the vertical coordinate measured from the bottom.

$$F_C = \int_0^R \rho_0 r\, \Delta(\omega^2)\, dr \qquad (3)$$

where R is the radius of the cylinder, and r is the radial coordinate measured from the axis. In Eq. 3, the pressure gradient has been set equal to the difference between the centrifugal force in the boundary layer and the centrifugal force in the bulk liquid; consequently, $\Delta(\omega^2)$ may be taken as the difference between the squares of the initial and final velocities of the turntable.

The experiment is performed by placing a cylindrical container of fluid on a turntable, allowing it to come to equilibrium, and then introducing a differential rotation by slowing down the container. The convective currents arising in such a system are called "Ekman pumping" (*5*), and the movement of tea leaves into the center of a cup of stirred tea is an example of this phenomenon. Our experiment, although essentially the same as that of McDonald and Dicke (*3*), was designed to determine whether the actual density gradient inside the sun is large enough to suppress convection. To this end, we were interested in verifying a simple force-balance argument which would determine quantitatively the transition point between convective and viscous spin-down.

Stock solutions of $Cu(NO_3)_2$ (1.20 g/cm^3) were diluted with distilled water to produce solutions with densities of 1.15, 1.10, 1.05, and 1.025 g/cm^3. Density-stratified solutions with values of ρ_0 that ranged from 1.2 to 1.025 g/cm^3 were compared with uniform-density solutions of the same mean density. Changes in the angular velocity ranged from 0.15 to 4.91 rev/min with all runs having an initial angular velocity of 18.7 rev/min.

The density-stratified fluids were prepared by pouring the fluids into the container over a small hollow petri dish lid that was allowed to float in the fluid. The density variation could thus be established in layers and then carefully mixed by hand to provide a uniform density gradient. The actual density profile was measured before and after each run with a photometer that was driven slowly down into the fluid at a constant rate. The photometer was calibrated directly against stock solutions so that the optical transmittance and consequently the density were given as functions of z. Density profiles approaching linearity were established before each run. The process of bringing the container up to its equilibrium velocity and stopping generally degraded the profile but did not destroy it. The average density gradient was normally reduced by about 50 percent. The density-stratified fluids were quite stable against diffusion. Once prepared, they would last many hours if left undisturbed.

The only fundamental difference between our experimental setup and that of McDonald and Dicke was the alignment with the gravitational vertical. They maintained the axis of the container parallel to the gravitational vertical to within 1 second of arc to eliminate the small constant-velocity residuals which are established in the fluid if the container is tilted. In our experiment, the alignment was maintained to within 10 seconds of arc, with the velocity residuals measured immediately before a run and added algebraically to the motion of the fluid.

Our experimental objective was to locate the region of transition between convective and viscous angular-momentum loss. For the experiment of McDonald and Dicke, Eqs. 1 and 3 indicate the buoyancy force to be about 35 times the convective force. This ratio can be reduced by decreasing the density gradient, decreasing the height of the liquid, or increasing the change in angular velocity. Our approach was to vary the values of the density from 1.05 g/cm^3 at the bottom to 1.00 g/cm^3 at the top, and to reduce the height of the liquid until the transition between viscous and convective flow occurs. The results are shown in Fig. 1. The upper and lower curves correspond to viscous and convective angular-momentum transfer, respectively; the intermediate curves represent the transition region, where the buoyancy and convective forces are almost equal. It appears from the shape of some of the curves in the transition region that there is a tendency for convection to occur initially and then for the flow to stabilize after approximately 100 seconds. This behavior can be observed in an oil-liquid system in which the interface initially is seen to rise in the center of the cylinder with depression at the edges, and to continuously rise until a stable configuration is reached which prevents further convection.

The relation between spin-down and force ratio is shown in Fig. 2. The decay-time constant, $1/T$, determined from Eq. 4 by angular-displacement measurements between 10 and 100 seconds, is plotted as a function of the force ratio F_B/F_C calculated from Eqs. 1 and 3. In Eq. 4 θ is the azimuthal position of the marker float at a given time t, ω_0 is the initial angular velocity, and ω_1 is the final angular velocity of the turntable.

$$1/T = -\frac{\ln(\Delta\theta/\Delta t)}{t} + \frac{\ln(\omega_0 - \omega_1)}{t} \quad (4)$$

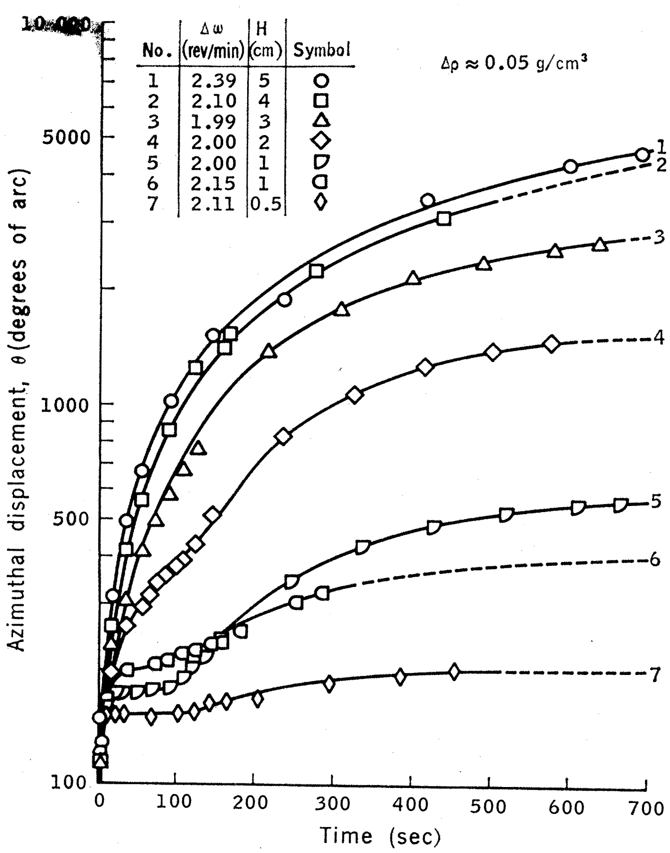
The horizontal brackets (Fig. 2) indicate the range in the force ratio resulting from calculations of F_B based on the density gradient before and after each test. The vertical brackets indicate the uncertainty in $1/T$ as a result of the departure of the curves from truly exponential form. We conclude that the transition between viscous and convective angular-momentum loss occurs near the point at which the buoyancy force given in Eq. 1 equals the convective force given in Eq. 3.

A similar force-balance calculation can be performed for the sun. However, because the solar material is compressible, account must be taken of the expansion of the solar plasma as it rises. Therefore, the bouyancy force is the difference between an adiabatic density profile and the actual local density, integrated along a radius from the center of the sun to the boundary of the fast-rotating region. In a similar analysis reported by Clark *et al.* (*6*), it is not clear whether the compressibility was taken into account. The results of these force-balance calculations for Solar Model J of Sears (*7*) show that the buoyancy force tending to suppress convection is approximately 1500 times larger than the pressure-gradient force driving the convection. The forces were calculated from Eqs. 5 and 6,

$$F_{B\odot} = \left[\sum \frac{(M_r/M_\odot)\,\Delta(r/R_\odot)\,\Delta\rho}{(r/R_\odot)^2}\right] \times (M_\odot G/R_\odot) \quad (5)$$

$$F_{C\odot} = \left[\sum \rho_m\,(r/R_\odot)\,\Delta\,(r/R_\odot)\right] R_\odot^2\,\Delta(\omega^2) \quad (6)$$

where ω, the angular velocity of the solar interior, is taken to be 1 rev/day; $\Delta\rho$ is the difference between ρ_m given by the Sears model and that of an adiabatic profile; $R_\odot$ is the radius of the sun; $M_\odot$ is its mass; G is the universal gravitational constant; r is the radial distance



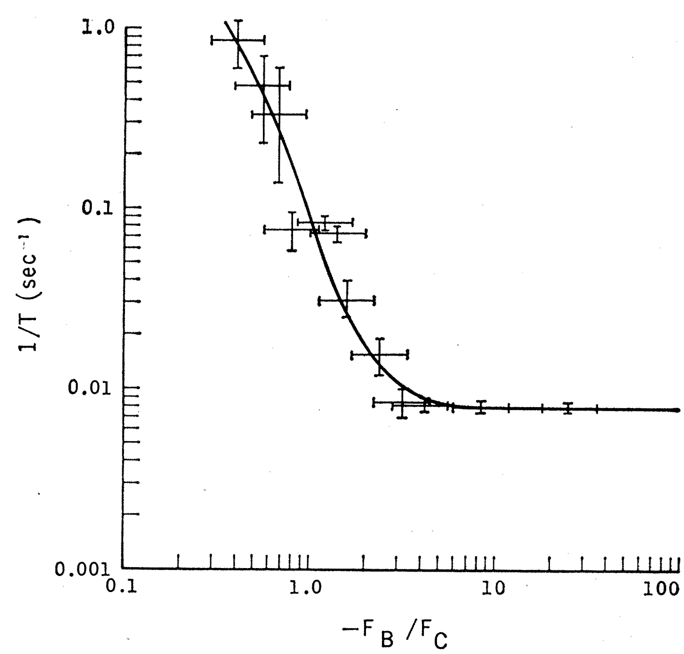


Fig. 1 (left). Angular displacement during spin-down for a density-stratified fluid with the specific gravity ranging from 1.05 at the bottom of the cylinder to 1.00 at the top. The shape of curves 4 to 7 is interpreted as resulting from an initial convection which stops before a turnover of the liquid is completed. Fig. 2 (right). Decay-time constant as a function of F_B/F_C. The vertical error bars represent the mean deviation of the decay constant with time for an individual curve from Fig. 1. The horizontal brackets indicate an uncertainty of a factor of 2 in the density gradient due to possible mixing during spin-up, which is reflected in the calculation of F_B.

of a fluid element from the center of the sun; and M_r is the mass of solar material enclosed by this same radius. Consequently, large-scale convection should not occur in the solar interior. The solar model assumed in Eqs. 5 and 6 is for a nonrotating sun. Rotation would have some effect on the density profile; however, this is not expected to change the basic result, namely, that the buoyancy force is much larger than the pressure gradient. We conclude that solar models with rapidly rotating interiors are stable against large-scale convection caused by "Ekman pumping."

Conclusions regarding the rotation of the interior of the sun also must be consistent with the overall loss of angular momentum. The torque on the sun caused by magnetic forces (*8*) gives a time constant for an exponential decay of the rotation of about 7×10^9 years. If it is assumed that the sun was formed rotating at high velocities, the present magnetic torque is sufficient to slow an outer layer, thus leaving the interior in rapid rotation. However, a somewhat stronger magnetic field early in the life of the sun ($\approx$20 gauss instead of the present 3 gauss), would have been sufficient to slow the entire sun to the presently observed angular velocity. The magnetic history of the sun is not known. The work of Wilson (*9*) on stellar emissions indicates a higher level of activity early in the life of stars, which may imply stronger magnetic fields. However, it is not possible to measure stellar magnetic fields as small as 20 gauss; hence there is no direct evidence. We conclude that the existence of a rapidly rotating interior is in accord with the solar angular-momentum loss.

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Circum-Pacific Late Cenozoic Structural Rejuvenation: Implications for Sea Floor Spreading

Abstract. *The hypothesis of sea floor spreading and lithosphere plates seems to unify the origins of both oceanic ridges and volcanic arc-trench systems; therefore knowledge of well-known land areas should shed light upon sea floor tectonics. Impressive evidence of a major mid-Cenozoic discontinuity in the tectonic history of circum-Pacific land areas suggests a roughly synchronous change in sea floor development, more evidence for which may be anticipated in the future.*

The widely acclaimed hypothesis of sea floor spreading, and especially its latest refinement, the lithosphere plate hypothesis, appears to be one of those rare simplifying generalizations of knowledge that provide powerful new bases for formulating and rapidly testing questions about the earth. According to this "new global tectonics" we should expect closer worldwide relationships among continents and between the sea floors and continents than we had reason to suspect before (*1, 2*). All movements of lithosphere plates should be so interrelated that "no mid-oceanic ridge can be understood independently of the others" (*2*). If true, then students of continental structure and history should be in a position to shed considerable light upon less-known sea floor history; well-known land areas should provide tests or refinements of postulated spreading histories.

Geologists long have been impressed by a profound change in land-sea relations, sedimentation, biota, and structural disturbances near the middle of the Cenozoic era (about 25 to 30 million years ago). Recognition a century ago of such contrasts in Europe is reflected in the formal divisions of the Cenozoic, Neogene and Paleogene. Well-known major extinctions and beginnings of changes in geographic distributions among land animals and plants in mid-Cenozoic times were related to inception of profound topographic and climatic changes. In addition, prominent late Cenozoic structural disturbances have been recognized on most continents. These include the principal activity of Afro-Arabian and Baikal (Siberia) rift systems, the Victoria Land "horst" (Antarctica), Rhine graben—all with associated volcanoes—the Auvergne (France) volcanoes, and widespread elevation of mountains and plateaus (*3*).

Many circum-Pacific continental and island arc regions contain evidence of a mid-Cenozoic (about 25 million years ago) discontinuity in structural disturbances and sedimentation, which has been noted by several authors (*4, 5*). It appears that such a change was essentially universal around the Pacific, and therefore should be reflected in the sea floor if the "new global tectonics" is correct. A major stratigraphic discontinuity (unconformity) occurs widely around the Pacific margin beneath upper Cenozoic strata, and a great increase of volcanism during the past 25 to 30 million years is almost universal. In various areas severe faulting, uplift, and some metamorphism and formation of granitic masses (plutons) occurred as well. A few well-documented regions are summarized briefly below with reference citations to the most accessible literature.

Northeastern Honshu, Japan, shows a striking discordance of late Cenozoic (post-Oligocene) structural patterns with early Cenozoic ones. A prominent unconformity marks the base of Miocene strata, and great volcanic activity has characterized the past 25 million years; granitic plutons also formed (*4*). It is inferred that the Japanese trenches subsided rapidly during the latter interval as well.

Indonesia was relatively quiescent structurally in early Cenozoic time, but major mountain building commenced about 15 to 20 million years ago (late Miocene). As in Japan, granitic plutons formed, extensive faulting and folding occurred, and extreme volcanic activity commenced (*6*); simultaneously, the Java-Sumatra trench subsided profoundly. In the New Guinea-Solomon-Fiji Island belt, Miocene rocks rest unconformably upon older ones, and great volcanism has characterized the past 25 million years (*7, 8*). In southeastern New Guinea, a slight discordance between late Cenozoic and older structures is reported (*7*). Major volcanic activity commenced in New Zealand about 25 million years ago as the great Alpine transcurrent fault was reactivated (or possibly initiated). Up to 15 km of uplift occurred along that fault just in the past few million years (*9*).

Cenozoic structural and stratigraphic