Experiments on Turbulent Viscosity in Planetary Cores

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Introduction:
- Spherical shell spin-up experiments deduce turbulent viscosity in convecting fluid, relevant to the dynamics of planetary cores
- Doppler velocimetry measures large-scale and local, turbulent flow fields
- Novel technique quantitatively characterizes turbulent processes in rotating fluids
- Extrapolated experimental results suggest, controversially, large effective viscosity values for planetary core fluids

Experimental Set-up:
- Laminar Spin-Up in a Sphere:
  \[ u_0(s,t) = s \Delta \Omega \exp \left( - \frac{E^{-1/2} \Omega^{-1} (1 - s^2)^{3/4}}{t} \right) \]
  Greenspan, 1968

  - \( \Delta \Omega \) = azimuthal velocity; \( s \) = cylindrical radius; \( t \) = time;
  - \( \Omega \) = change in rotation rate; \( E \) = Ekman number
  - \( v = v(x,y) \) where \( v \) = kinematic viscosity, \( \Omega \) = rotation rate
  - \( R = \) fixed spherical shell radius

  - Spin-up timescale varies as \( v^{-1/2} \)
  - Varies in space only as a function of cylindrical radius \( s \)

Isotropical Spin-Up Results:
- Upper Left: Doppler velocity vs. beam distance and time
- Lower Left: Exponential spin-up behavior at fixed beam distance
- Right: Exponential spin-up time vs. cylindrical radius
- Doppler measurements fit Greenspan's theory: inversion matches fluid viscosity to within 2%

Isotropical Spin-Up: 150 to 190 rpm

Coconvective Spin-Up Results:
- Upper Left: Doppler velocity vs. beam distance and time
- Lower Left: Spin-up response at fixed beam distances
- Right: Exponential spin-up time vs. cylindrical radius
- Greenspan's theory explains measurements but with an EFFECTIVE VISCOSITY ~40% greater than viscosity at average convecting fluid temperature

Effective Viscosity Inversions:
- Right: Effective viscosity deduced from convective spin-up experiments vs. local Reynolds number, \( Re \), which parameterizes convective turbulence in the bulk of the fluid
- \( Re \) from experiments of Aubert et al. (2001), made using same apparatus
  - Effective viscosity increases by more than 50% over molecular viscosity values
  - Quasilinear fit between effective viscosity and \( Re \), in agreement with Kolmogorov's theory of turbulence

Implications for Planetary Cores:
- Extrapolating effective viscosity results to Earth's core, where \( Re \sim 10^8 \), implies \( \nu_{\text{effective}} \sim 10^6 \) \( \nu \sim 1 \) m²/s
- Suggests turbulent values of Ekman \( E \sim 10^{-9} \) and of magnetic Prandtl \( Pm \sim 1 \) in planetary cores
- In geostrophic flows, the effective viscosity in the Ekman boundary layers increases with turbulence in the bulk of the fluid