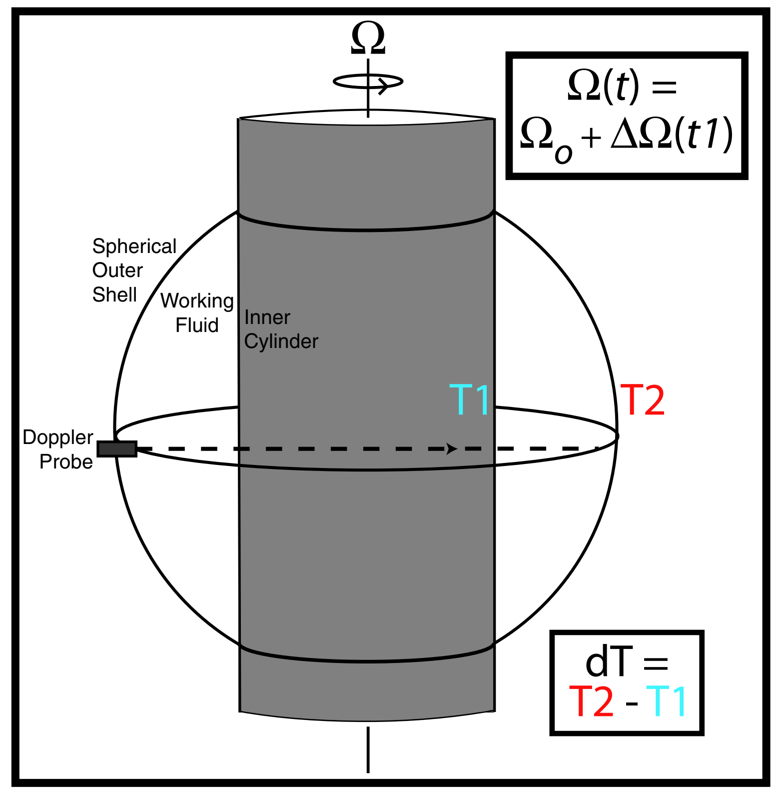
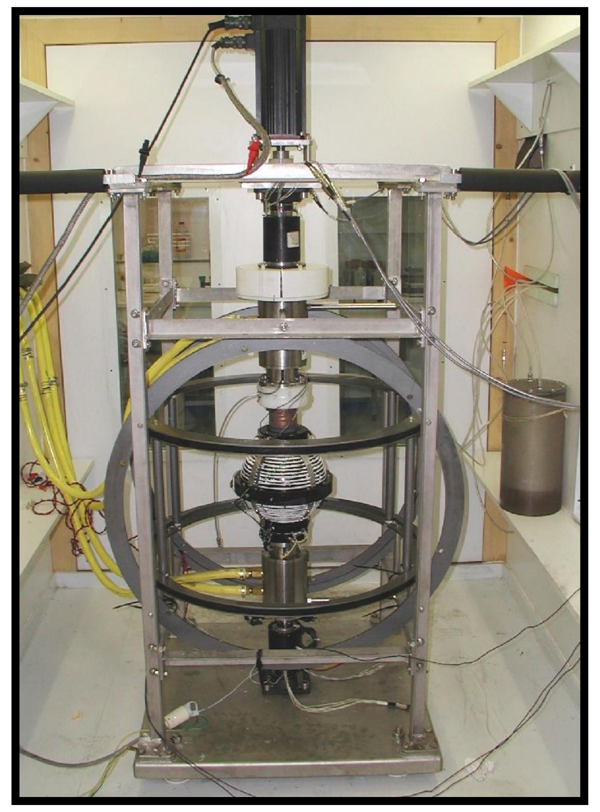
Experiments on Turbulent Viscosity in Planetary Cores

Daniel Brito[1], Jonathan Aurnou[2] and Philippe Cardin[1]
(email: Daniel.Brito@obs.ujf-grenoble.fr; jona@ess.ucla.edu; Philippe.Cardin@obs.ujf-grenoble.fr)
1 LGIT, Observatoire de Grenoble, France
2 DTM, Carnegie Institution of Washington, USA

Introduction:

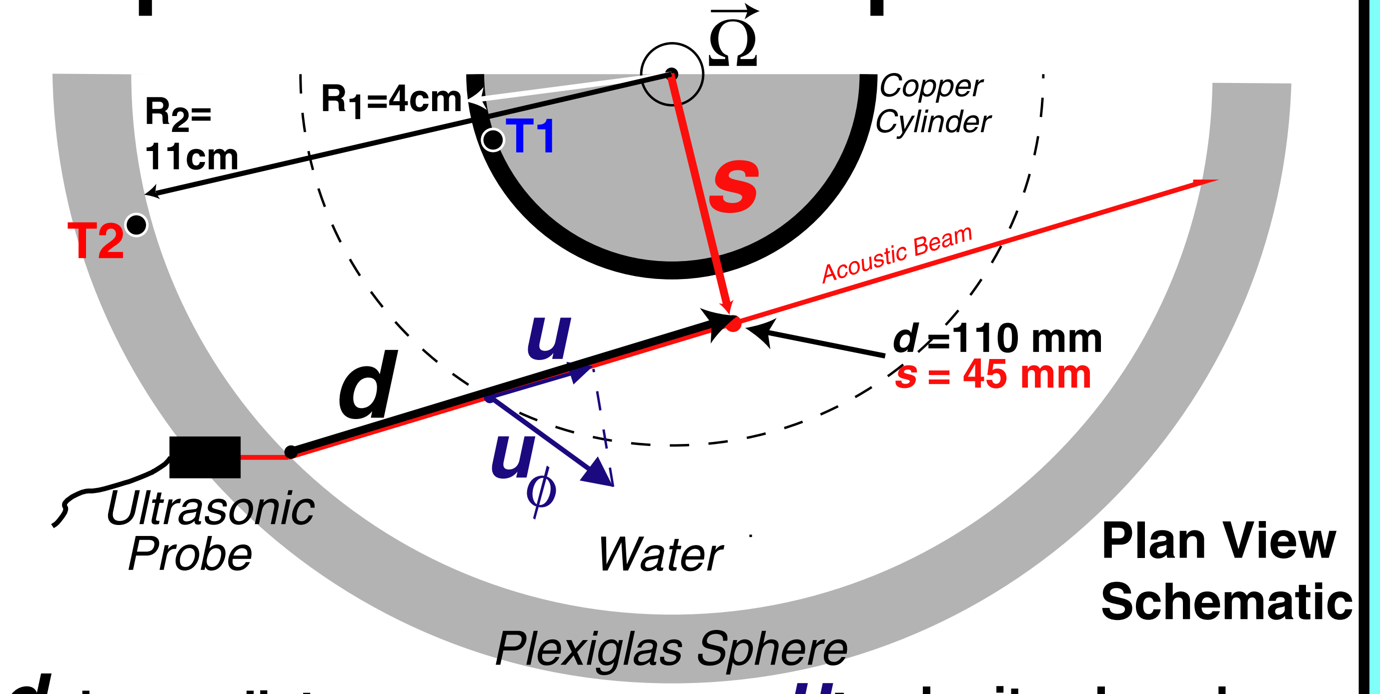


- Spherical shell spin-up experiments deduce turbulent viscosity in convecting fluid, relevant to the dynamics of planetary cores
- Doppler velocimetry measures large-scale and local, turbulent flow fields
- Novel technique quantitatively characterizes turbulent processes in rotating fluids
- Extrapolated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



Side View Photograph

Experimental Set-up:



Plan View Schematic

d: beam distance
s: cylindrical radius
u: velocity along beam
u_ϕ: azimuthal velocity

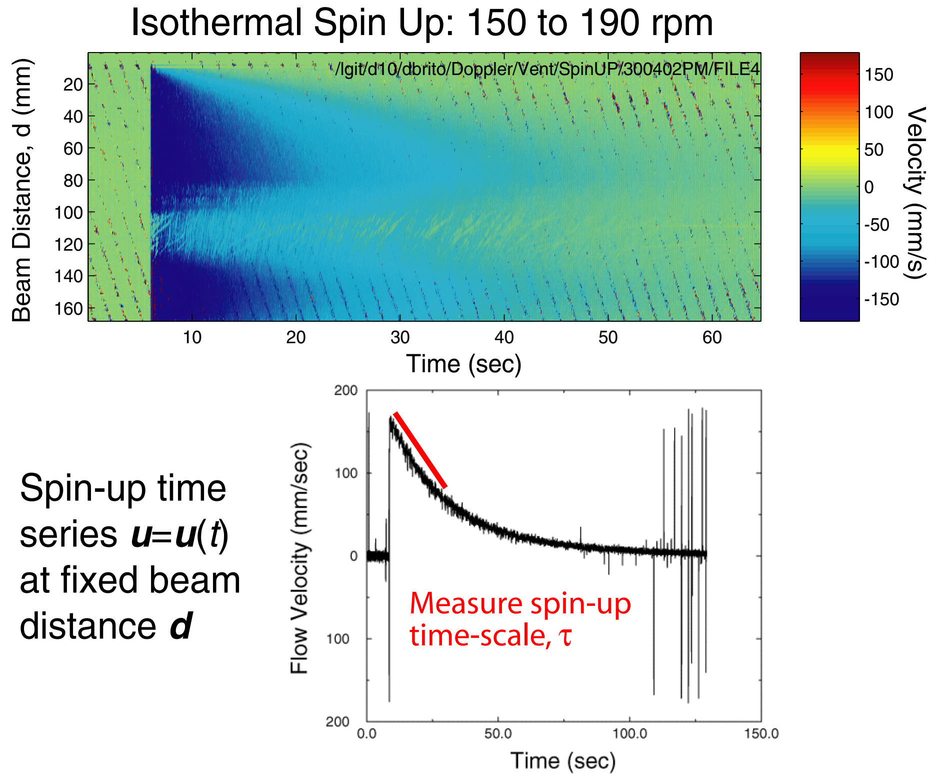
Laminar Spin-Up in a Sphere:

$$u_\phi(s,t) = s\Delta\Omega \exp\left[-\frac{t}{E^{-1/2}\,\Omega^{-1}\,(1-s^2/R^2)^{3/4}}\right]$$

Greenspan, 1968

- u_ϕ = azimuthal velocity; s = cylindrical radius; t = time; $\Delta\Omega$ = change in rotation rate; E = Ekman number $= \nu/\Omega R^2$ where ν = kinematic viscosity, Ω = rotation rate and R = fixed spherical shell radius
- Spin-up timescale varies as $\nu^{-1/2}$
- Varies in space only as a function of cylindrical radius s

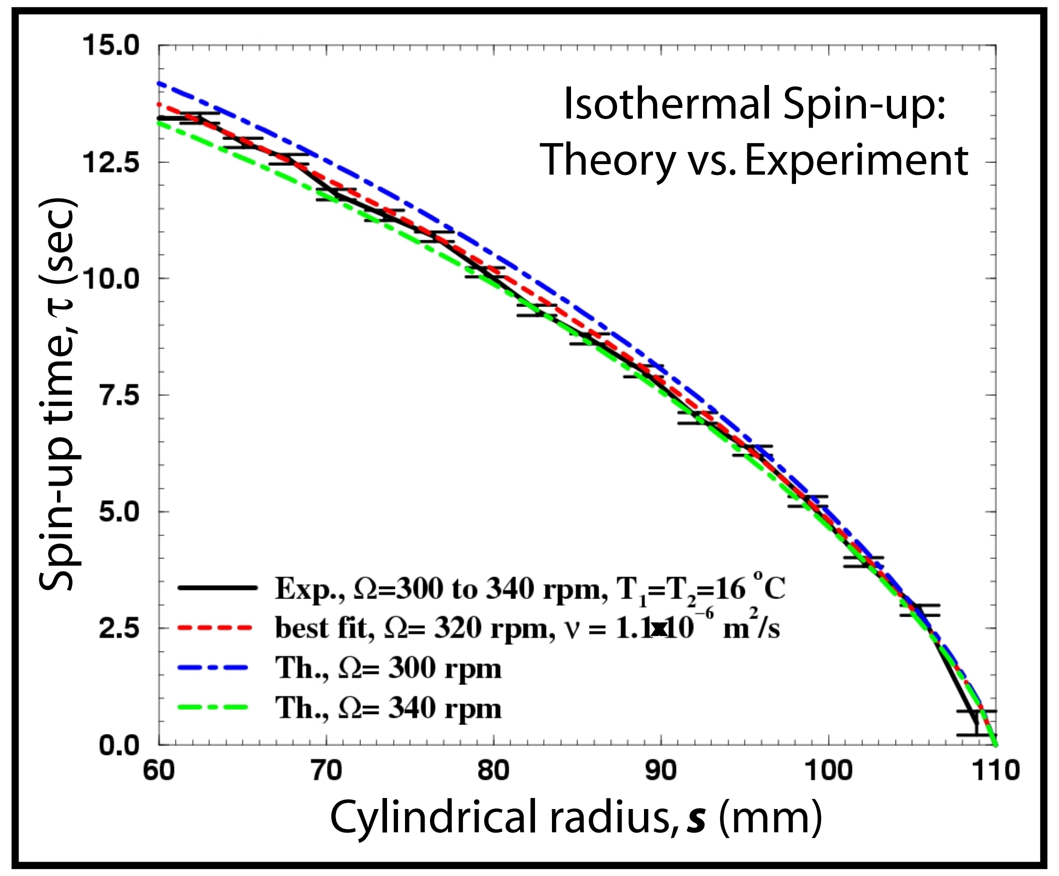
Isothermal Spin-Up Results:



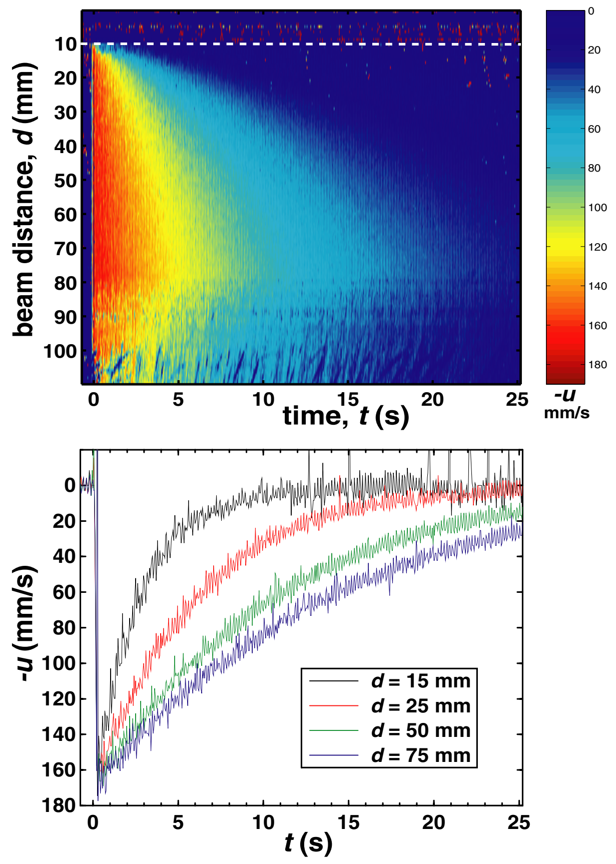
Spin-up time series $u=u(t)$ at fixed beam distance d

- **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%**

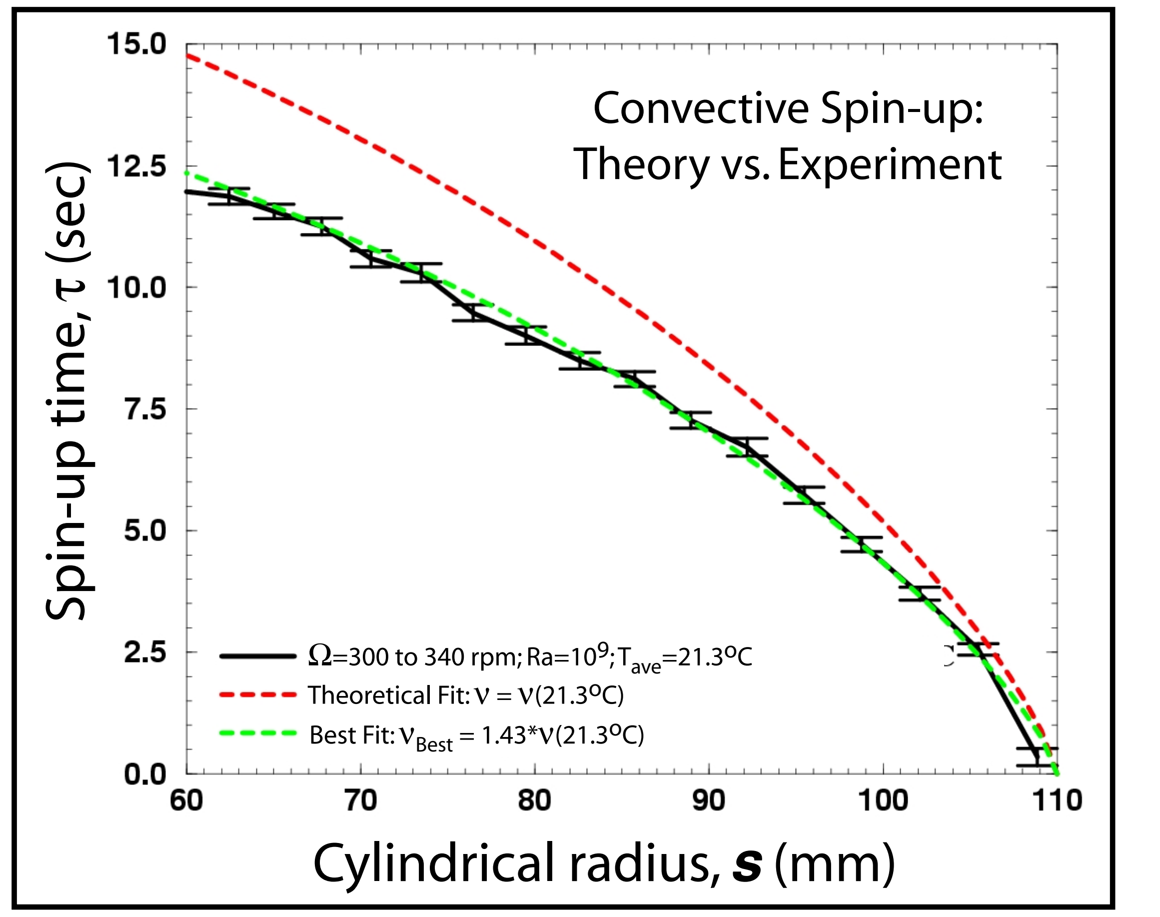


Convective Spin-Up Results:



- **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**

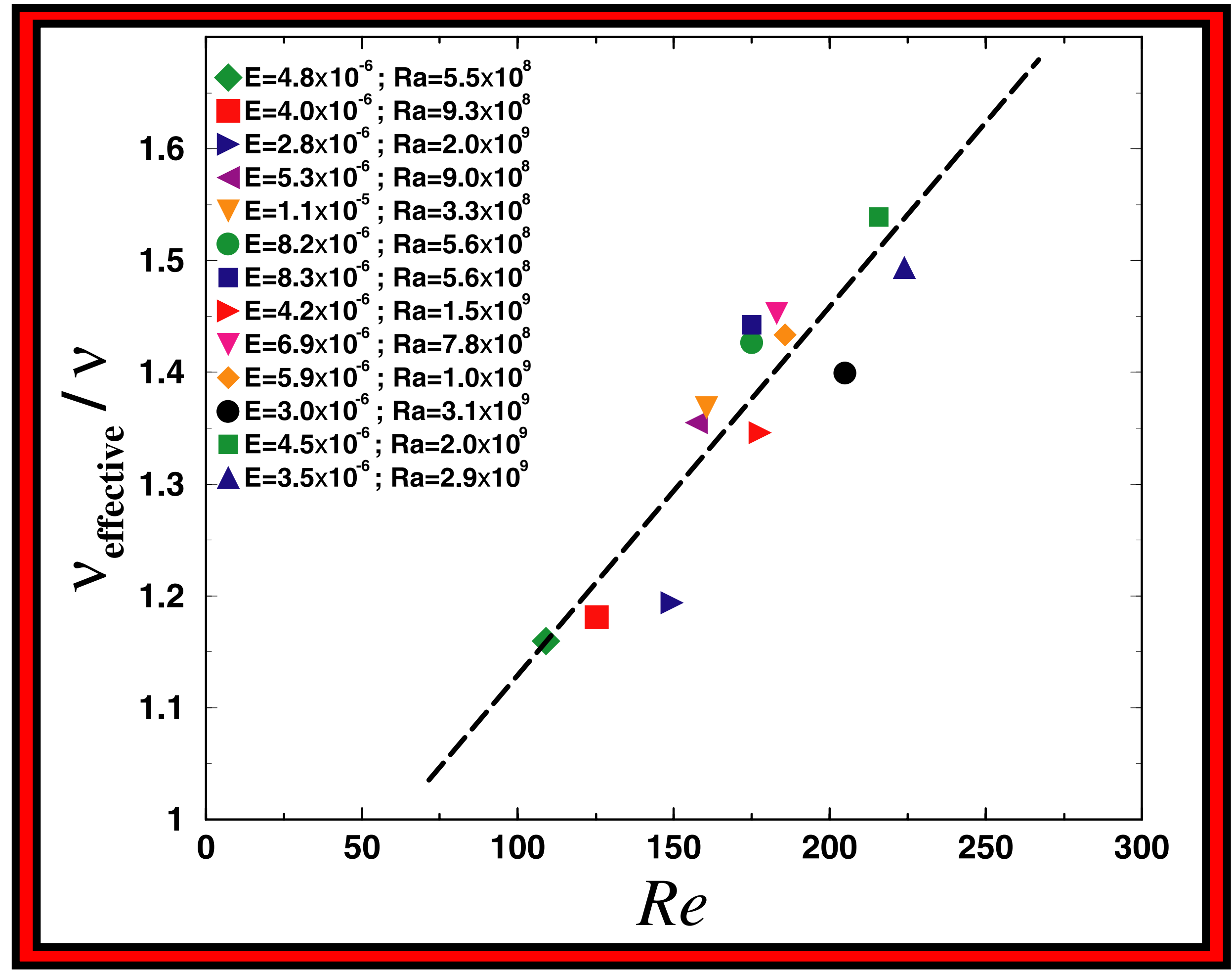


Effective Viscosity Inversions:

- **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 $\nu_{\mathrm{effective}} \sim 10^6\,\nu \sim 1\ \mathrm{m^2/s}$
- Suggests turbulent values of Ekman $\boldsymbol{E \sim 10^{-9}}$ and of magnetic Prandtl $\boldsymbol{Pm \sim 1}$ in planetary cores
- In geostrophic flows, the effective viscosity in the Ekman boundary layers increases with turbulence in the bulk of the fluid