What Are Neutron Stars?

Cold, stable gravitationally bound lumps

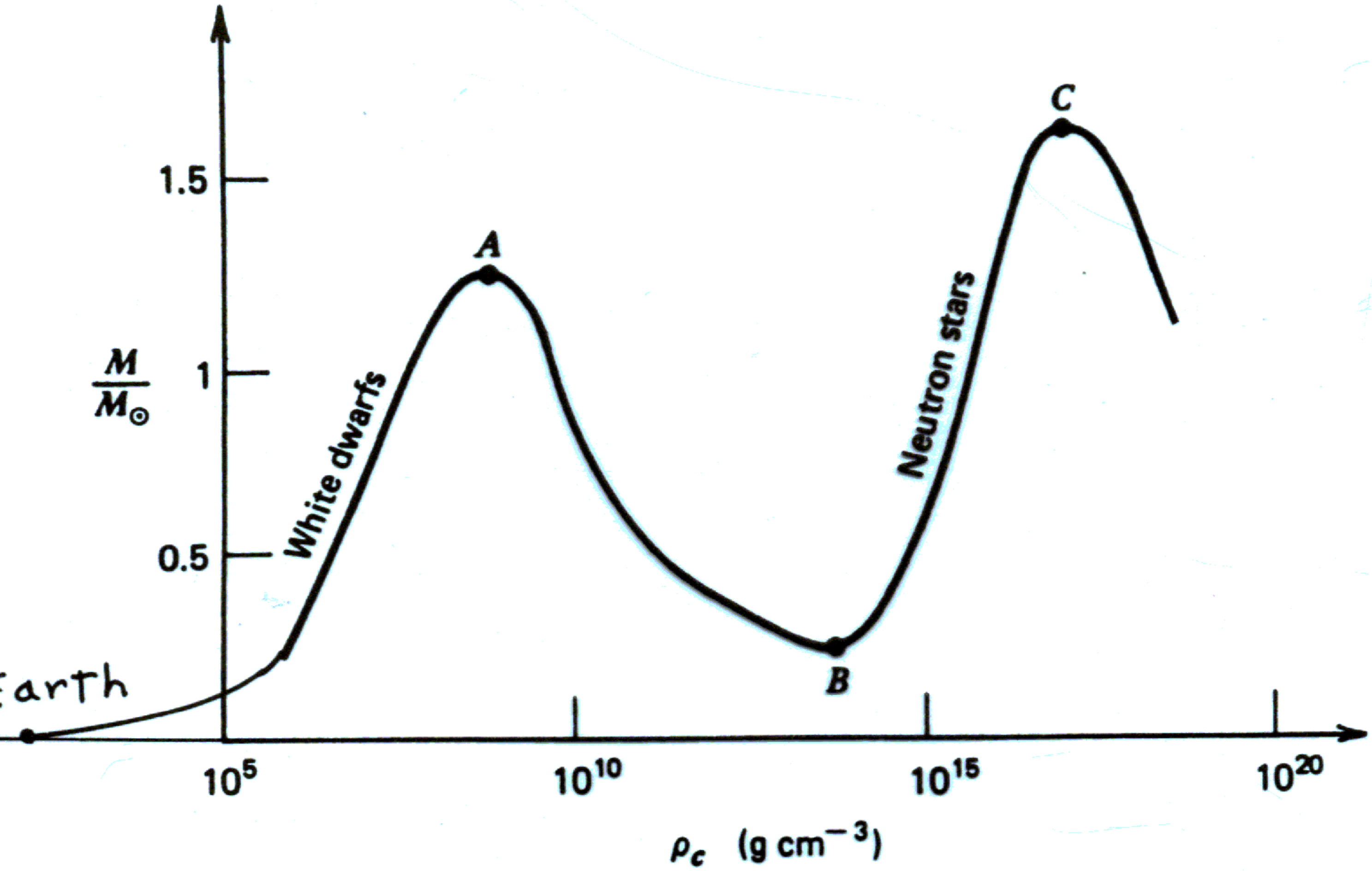
Relatives:
- Planets
- White dwarfs
- neutron stars
- black holes

Core-Crust Structure:
- Some family resemblance

MASSIVE "PLANETS"

"Planet" = Cold lump bound by gravity.

How massive can a planet be?



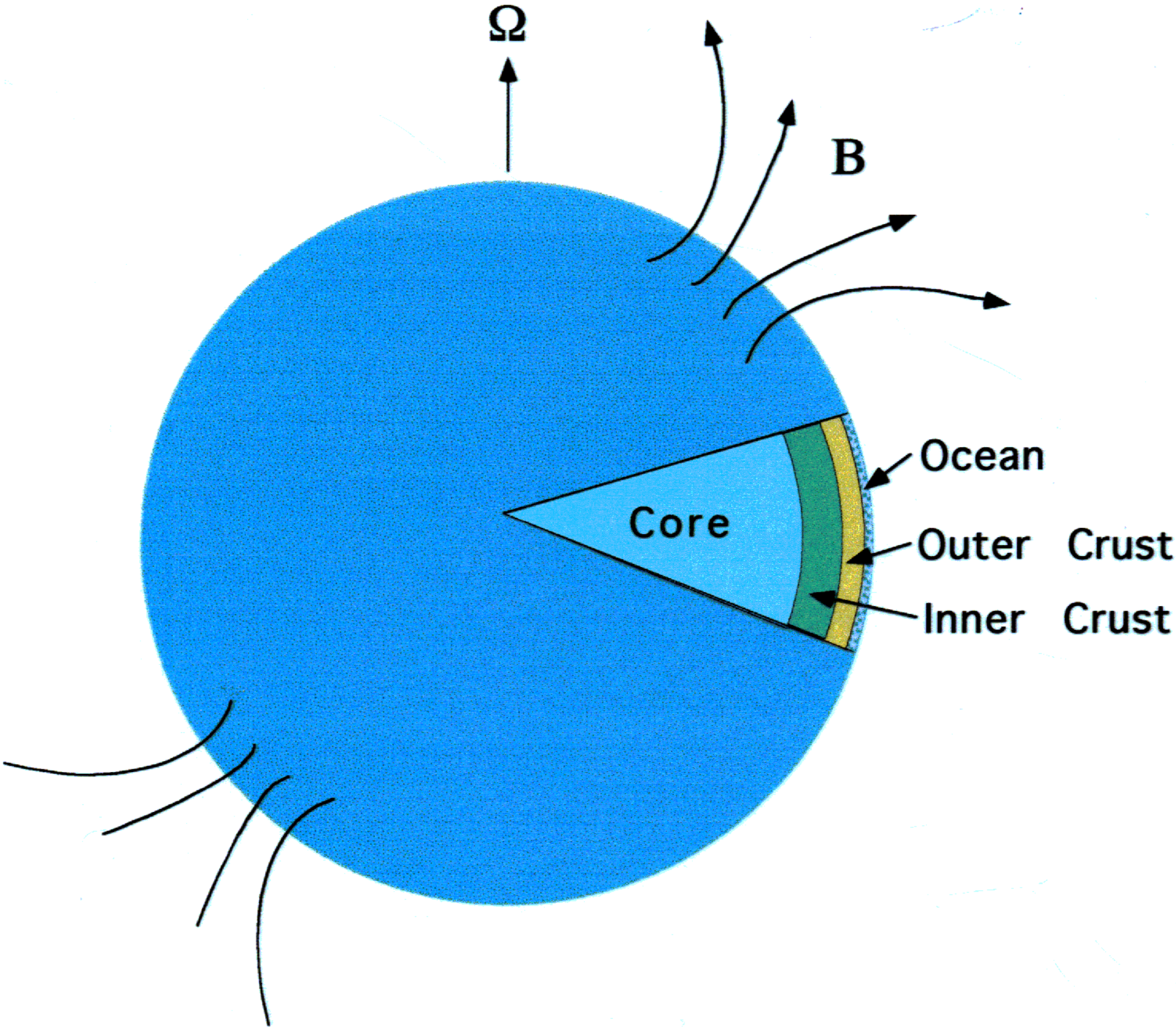
At high densities

$$e^- + p \rightarrow n + \nu$$

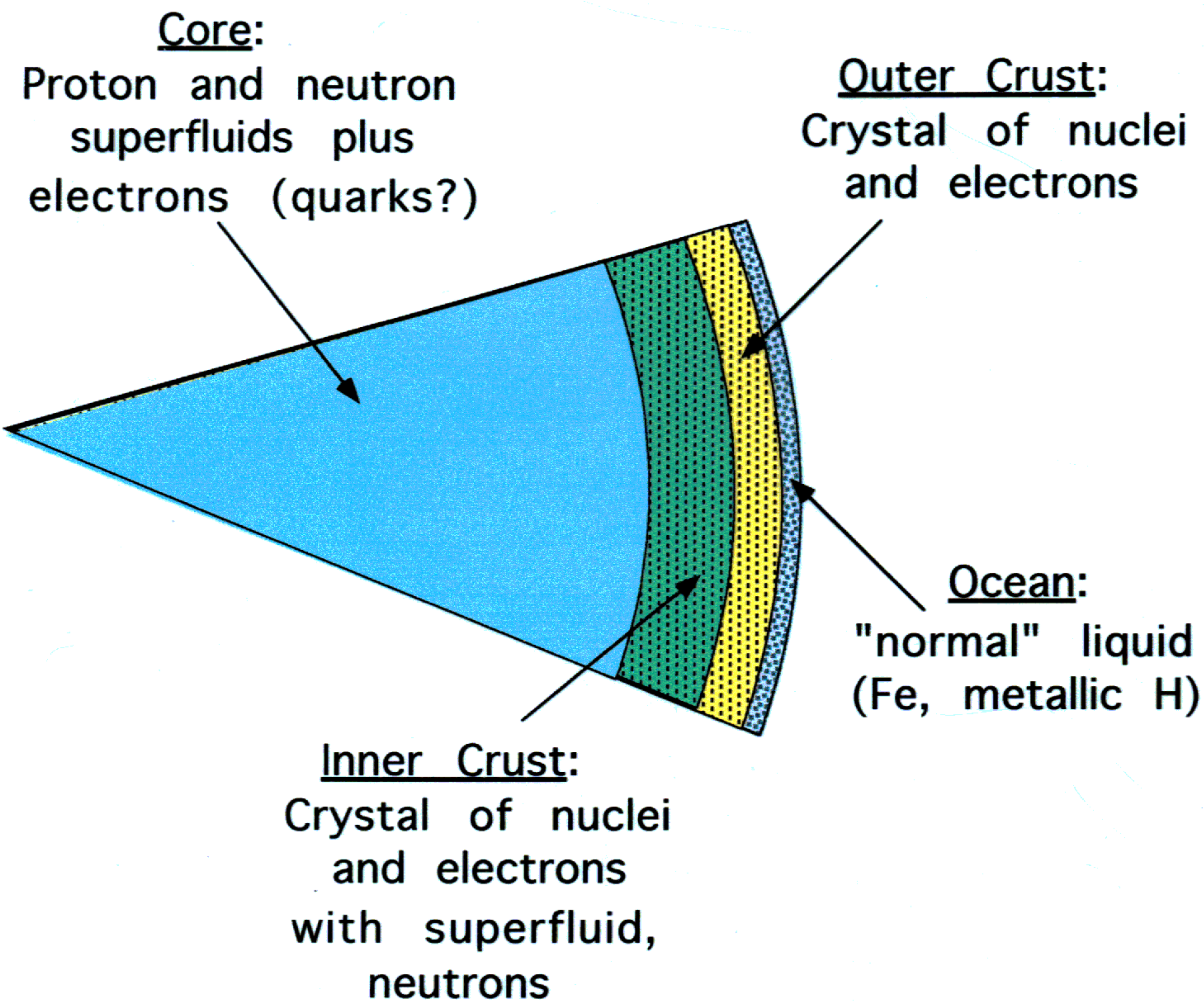
Neutron rich isotopes

Free neutrons

A Neutron Star

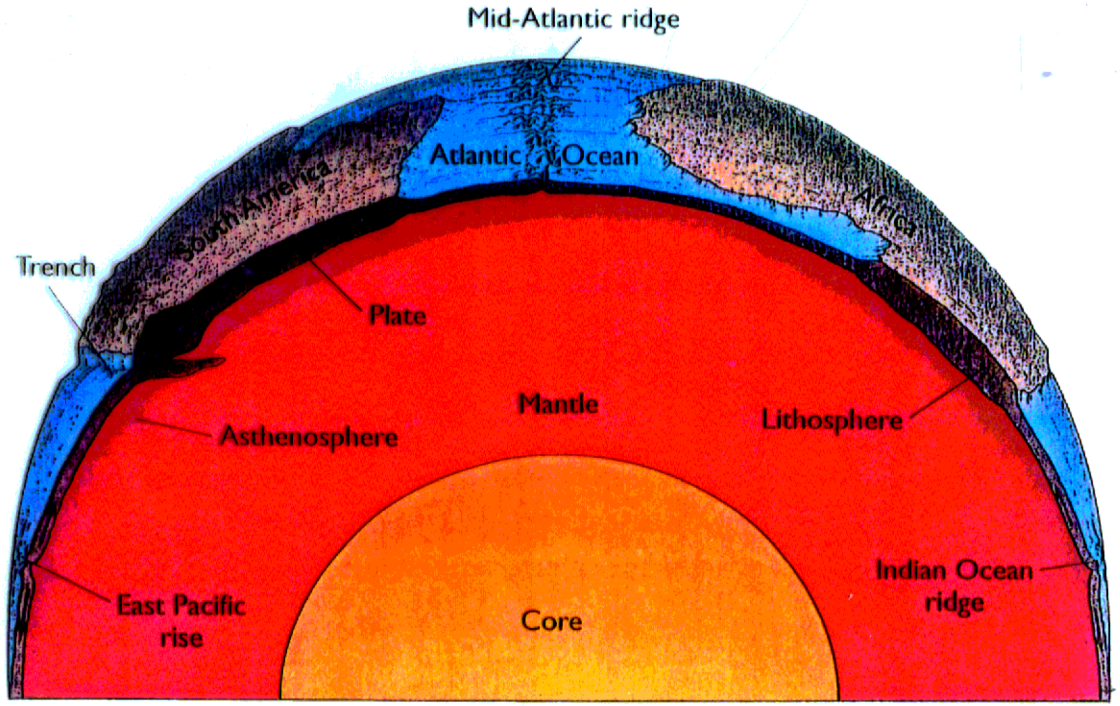


Neutron Star Structure

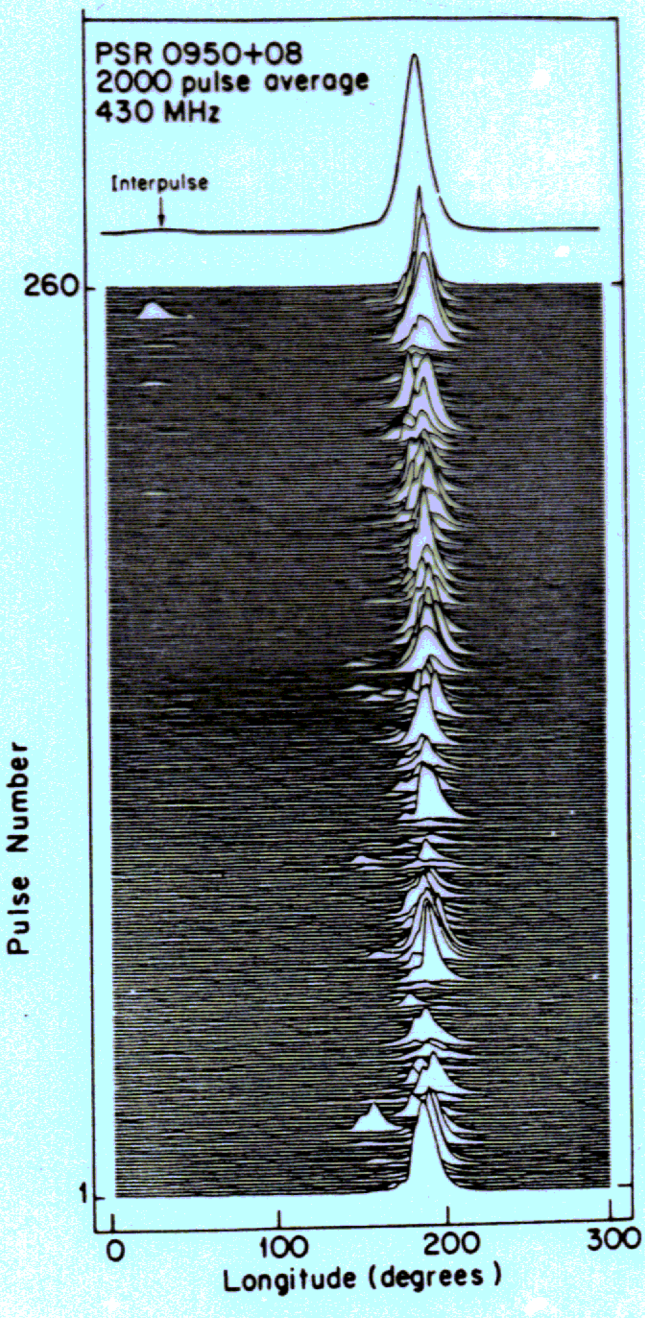


THE EARTH'S CRUST AND PLATES

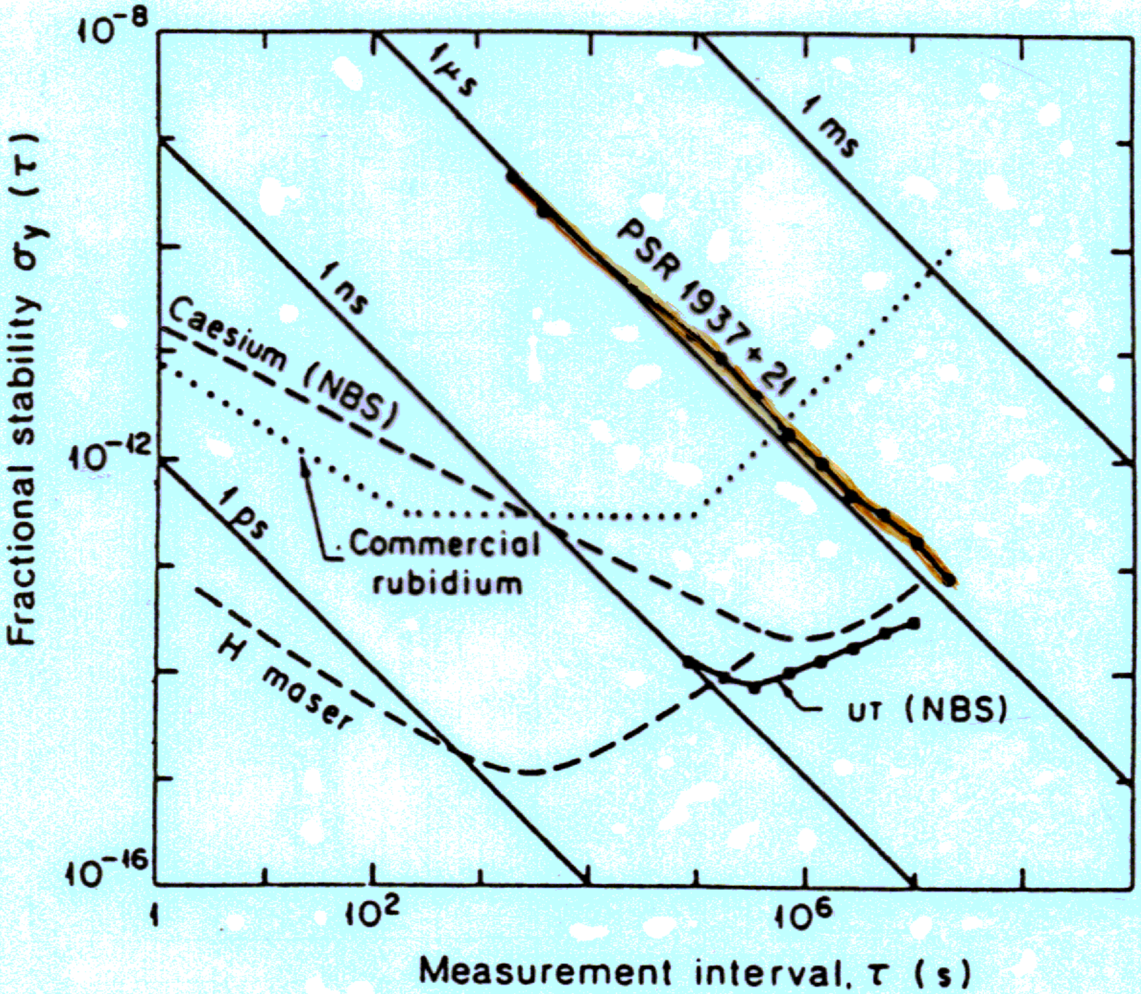
A rigid lithosphere of varying thickness floats on the softer asthenosphere. The lithosphere comprises tectonic plates moving in different directions. The African and South American plates separate along the Mid-Atlantic ridge at a rate of a few centimeters per year. The South American and Nazca plates converge to form the Andes Mountains. The thickness of the lithosphere and the asthenosphere is exaggerated so that they can be shown at this small scale.

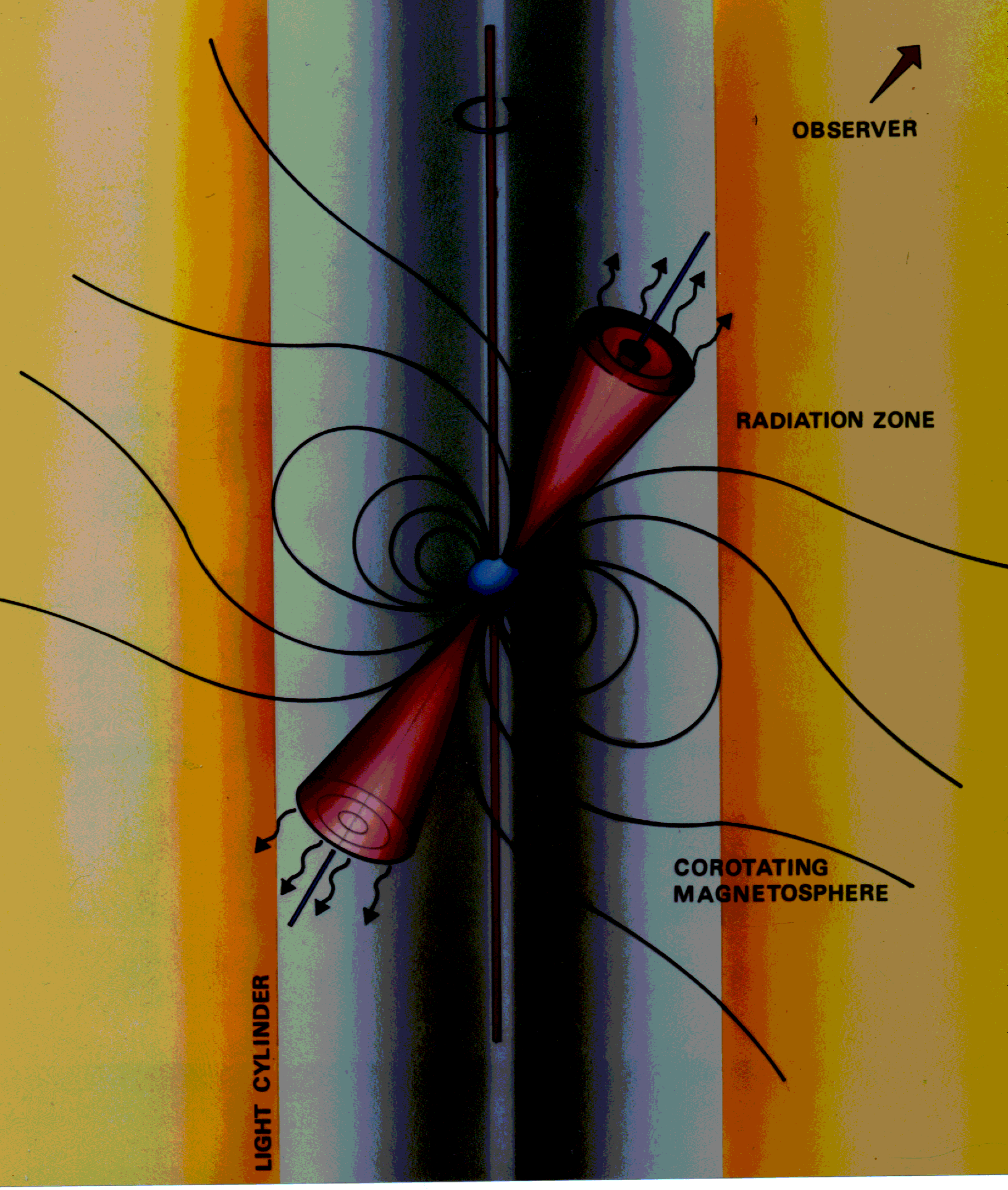


Average pulse shapes are very stable



Pulsars are superb clocks over long time scales





OBSERVER
RADIATION ZONE
COROTATING
MAGNETOSPHERE
LIGHT CYLINDER

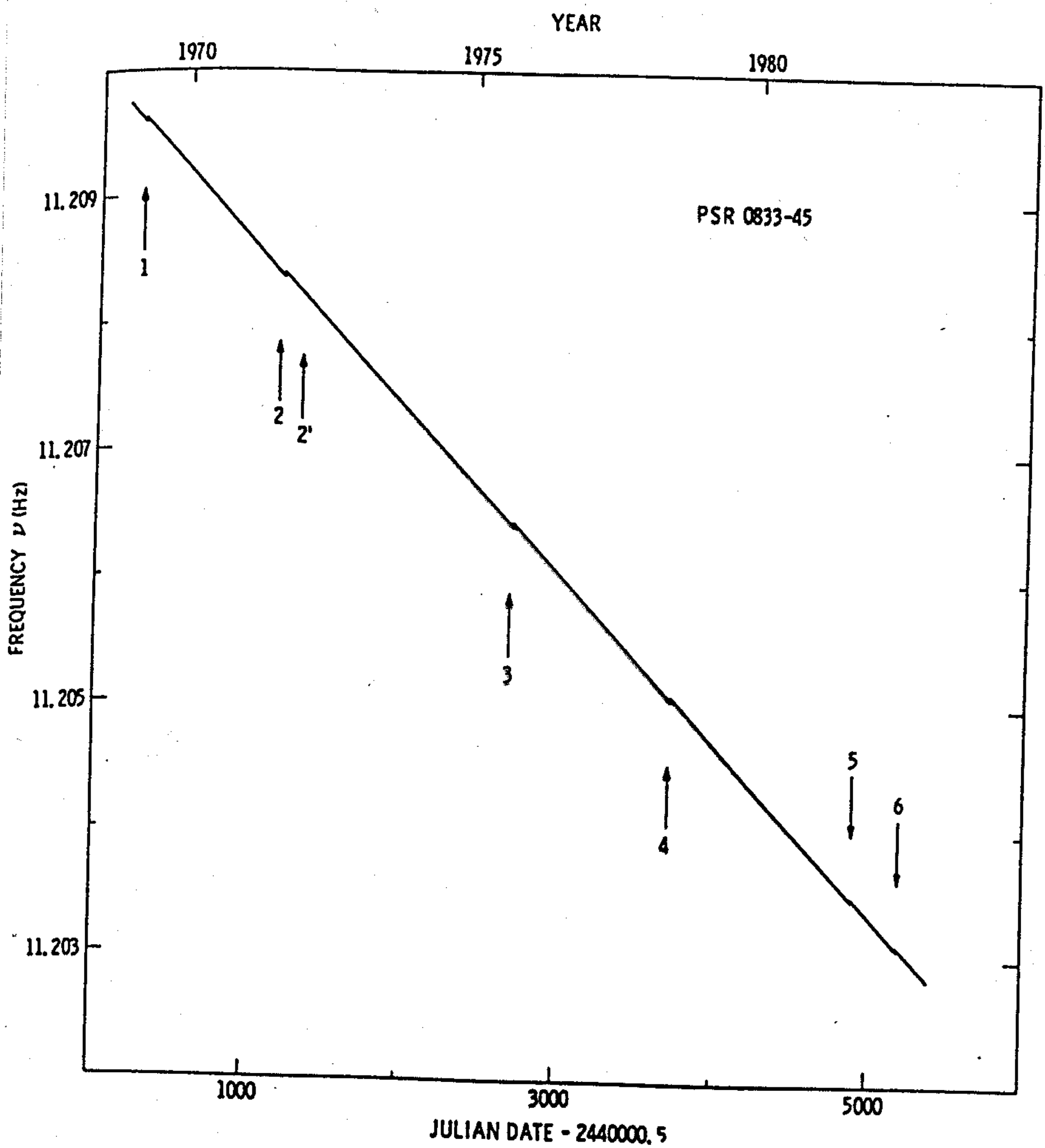
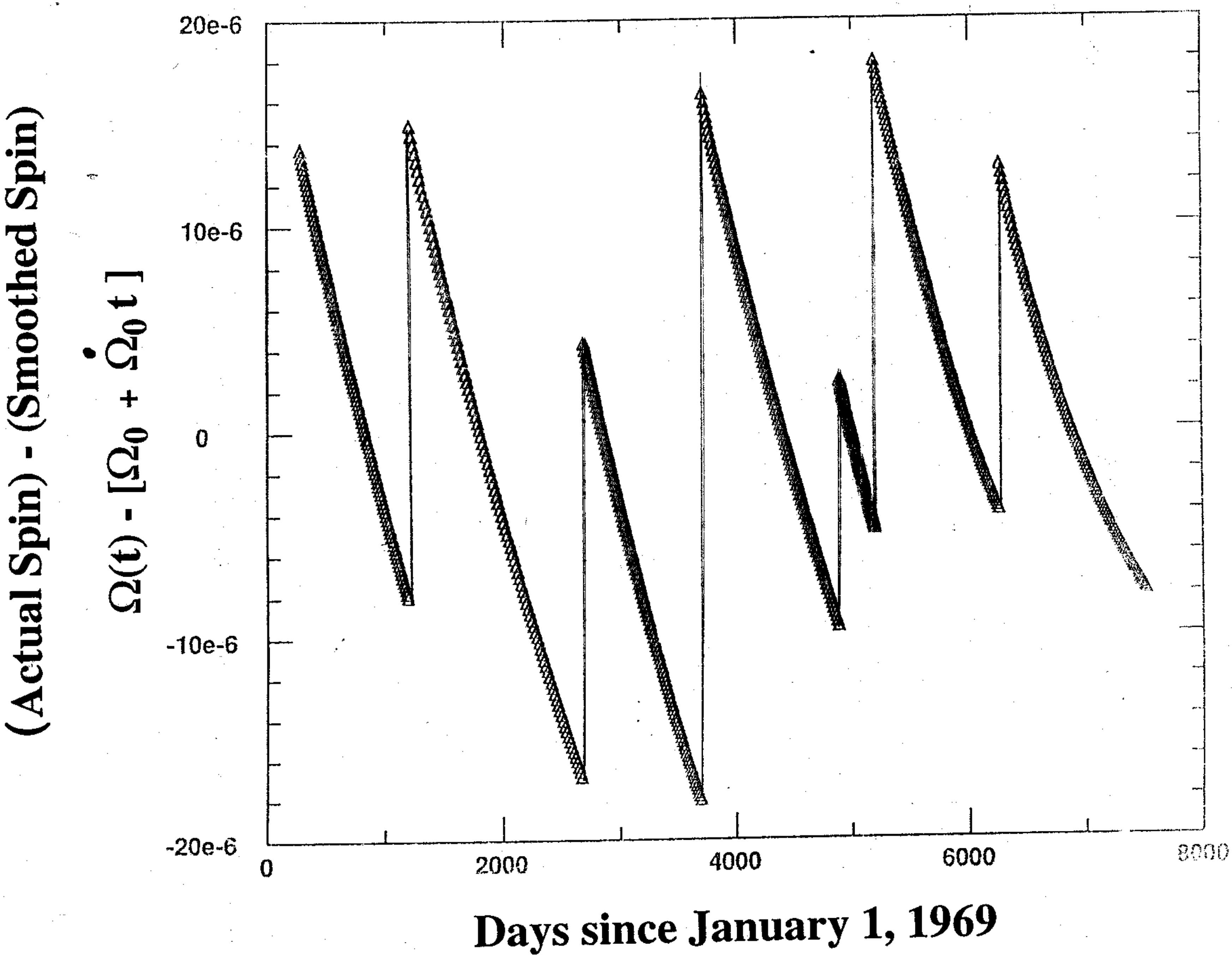
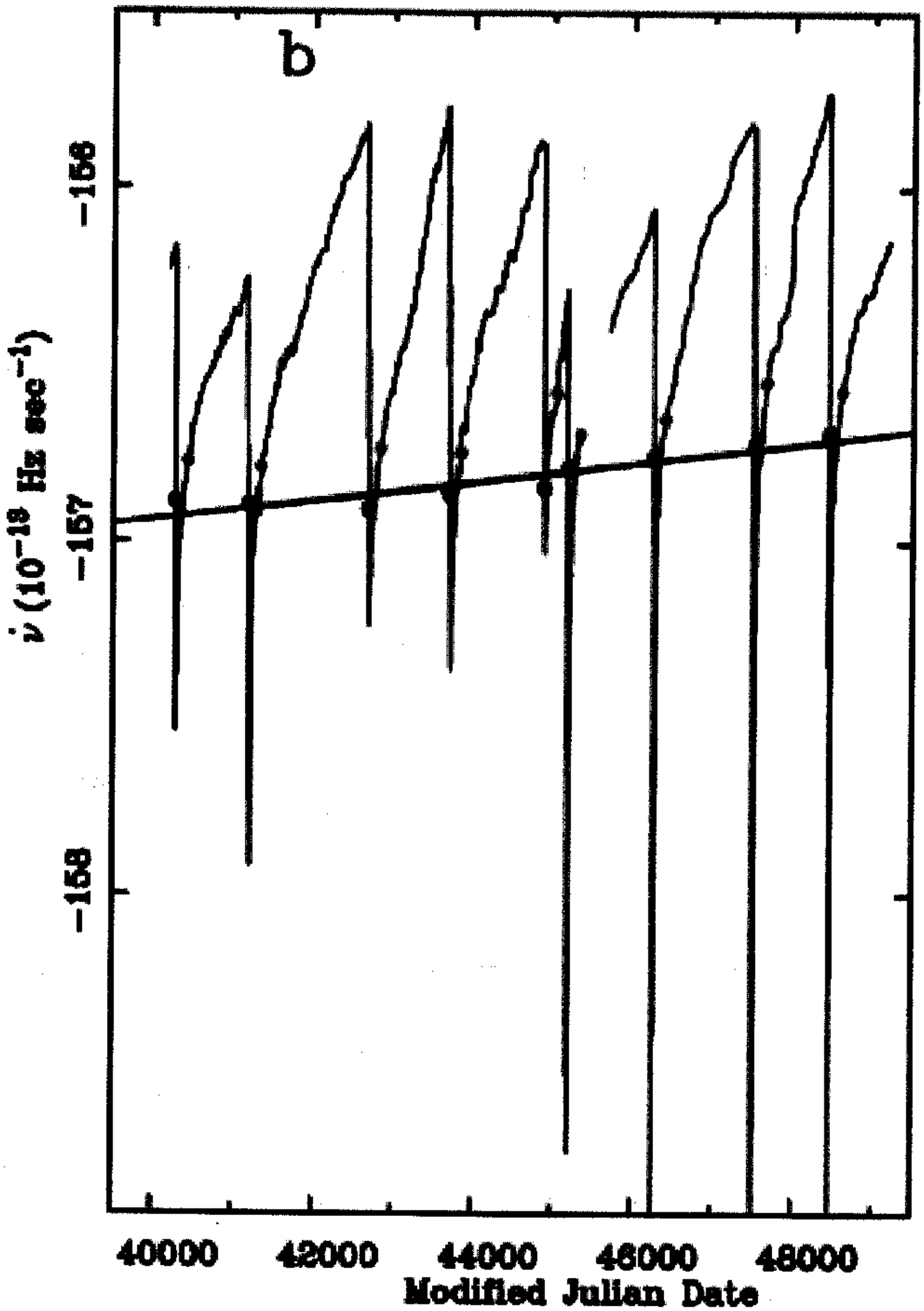


FIG. 1.11. Vela pulsar glitches. For $n = 3$ this curve should be a section of a parabola ($P^2 \approx t$) rather than a straight line; however, the deviation would amount to only about 1 part in 10^{-3}, too small to be seen on this scale and obviously small compared to the variations introduced by the glitches. From J. M. Cordes, G. S. Downs, and J. Krause-Polstorff, 1986, *Ap. J.*, 330, 847.

SPIN RATE OF THE VELA PULSAR



Vela Pulsar Spin History



1975 Glitch of the Crab

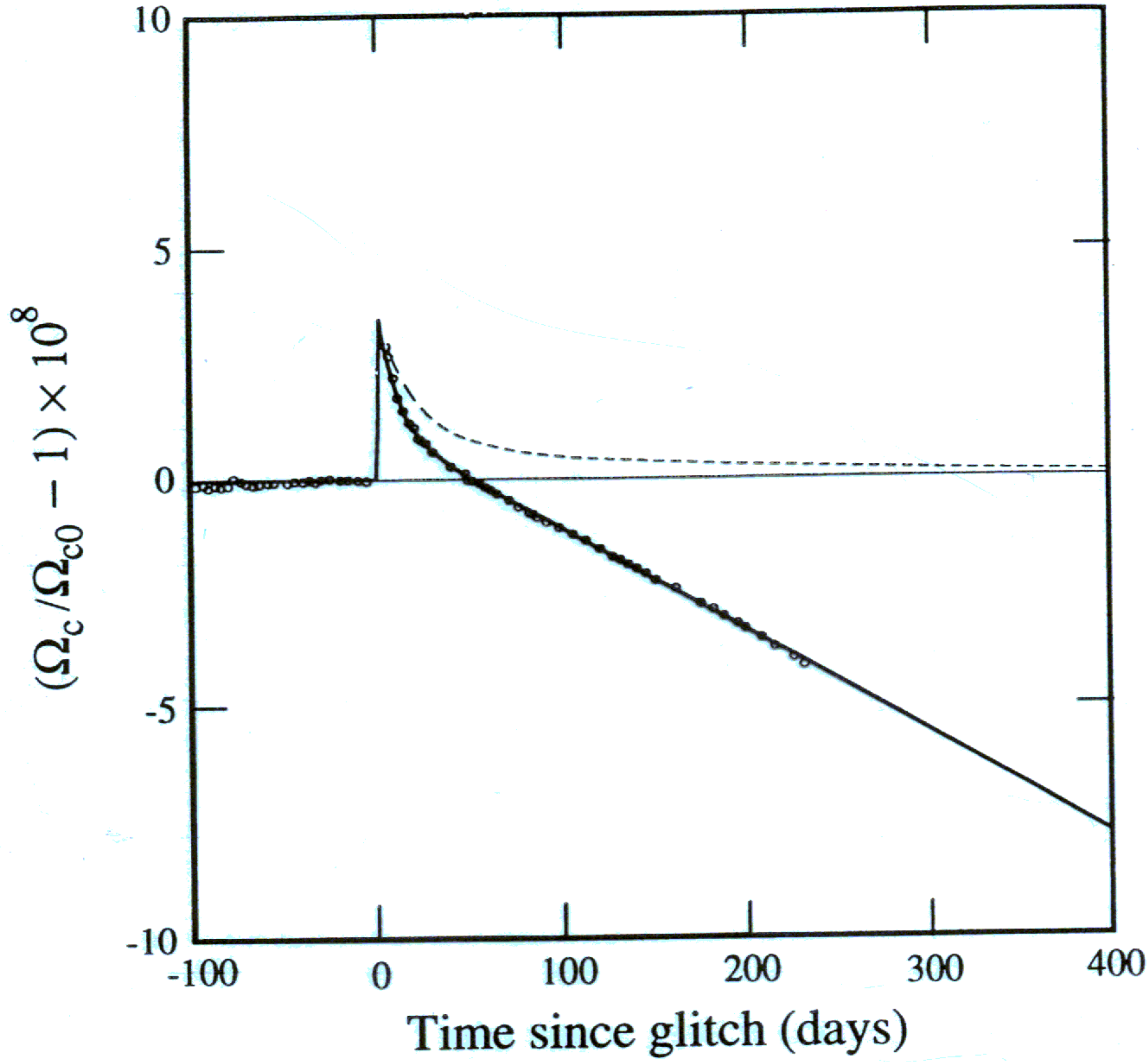
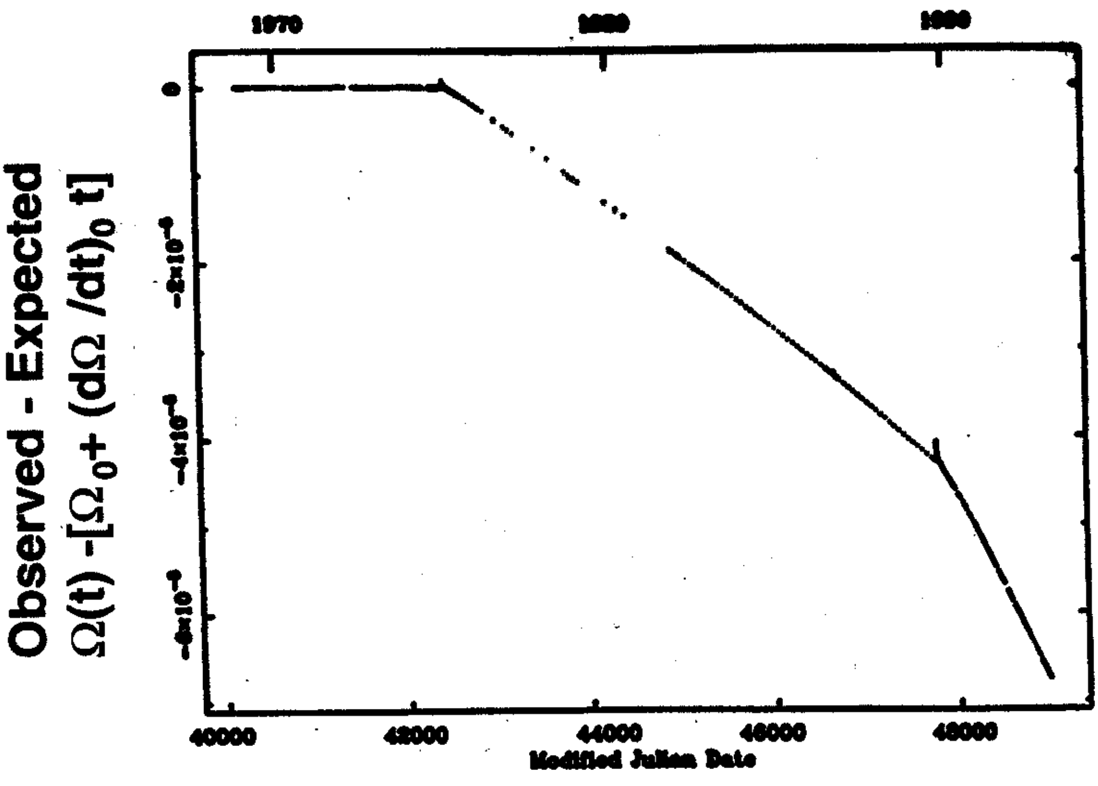


FIG. 1.—Spin evolution of the Crab pulsar following the 1975 February 4 glitch. The circles show the observed frequency residuals $(\Omega_c/\Omega_{c0} - 1)$ reported by Lohsen (1981), and the solid line is Lohsen's fit to these residuals. The dashed line illustrates the response of the crust in the vortex creep model assuming constant external torque and moments of inertia of the crust and superfluid; this model cannot exhibit a frequency deficit.

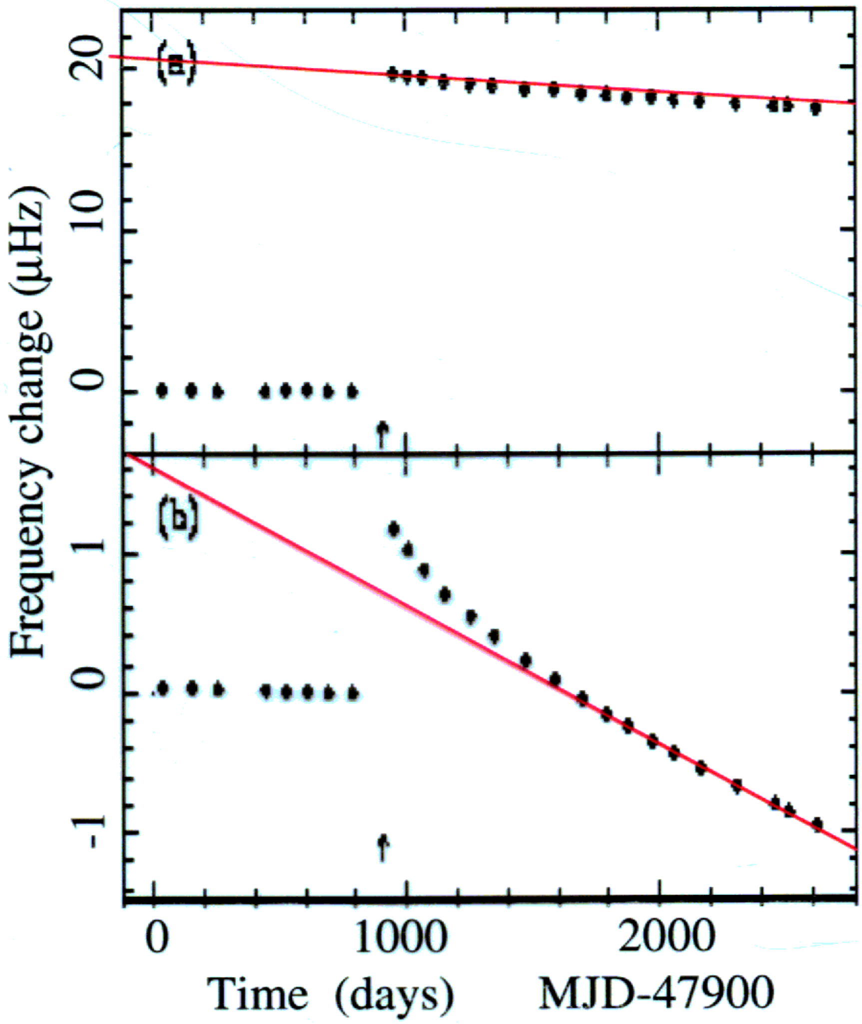
long-term change in $\dot{\Omega}_{crust}$

due to change in Torque.

CRAB PULSAR SPIN CHANGE

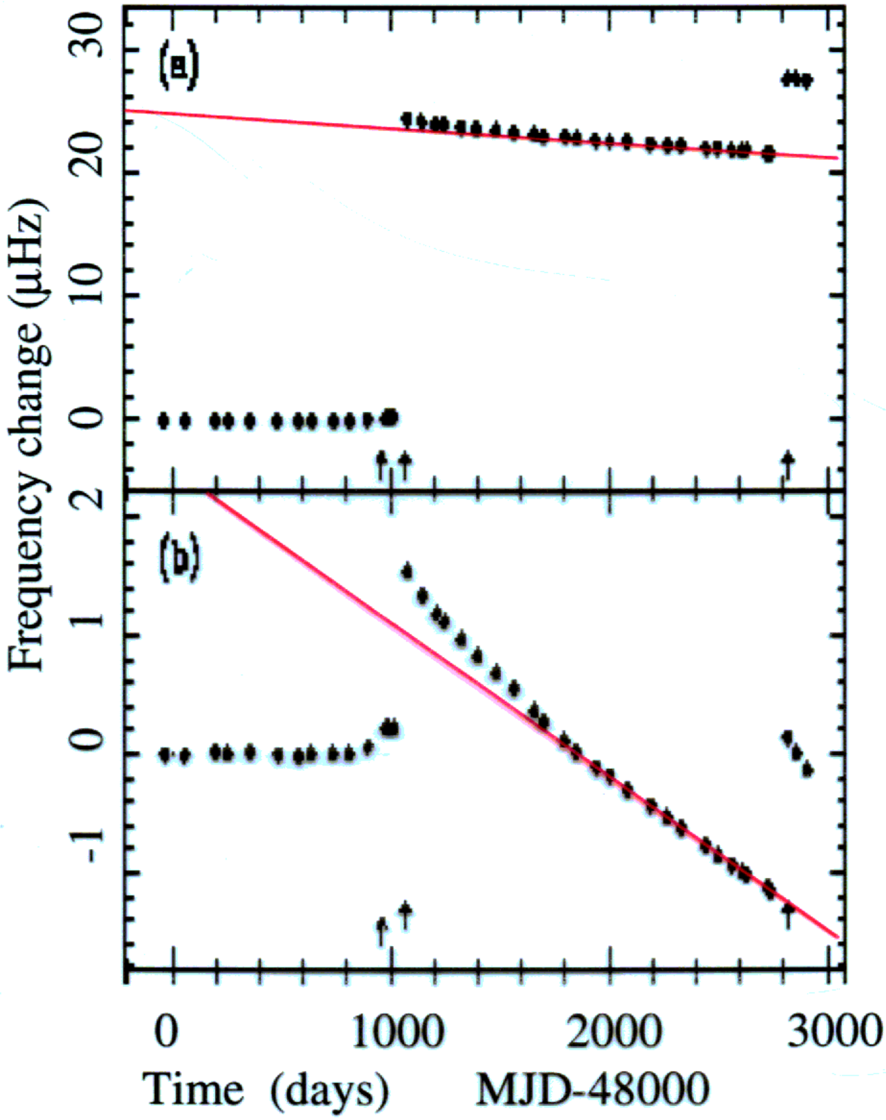


PSR J1709-4428



Wang et al. astro-ph/0005561

PSR J1048-5832



Wang et al. astro-ph/0005561

ORIGIN OF SPIN FLUCTUATIONS
"Glitches"

Something has to be out of equilibrium

Quake models: The shape of the star is too oblate (it formed when the star spun more quickly). A glitch is due to a decrease in the moment of inertia.

Flywheel models: Part of the star is "loose" and is spinning more rapidly than the crust. A glitch is caused by a sudden transfer of angular momentum from this loose part to the crust.

"Traditional" starquake-induced glitches

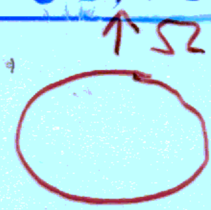
As a star spin slower, its equatorial bulge shrinks, and moment of inertia decreases:

$$I = I_0[1 + \varepsilon(t)]$$

Because the crust is rigid, $\varepsilon(t)$ decreases in steps: starquakes

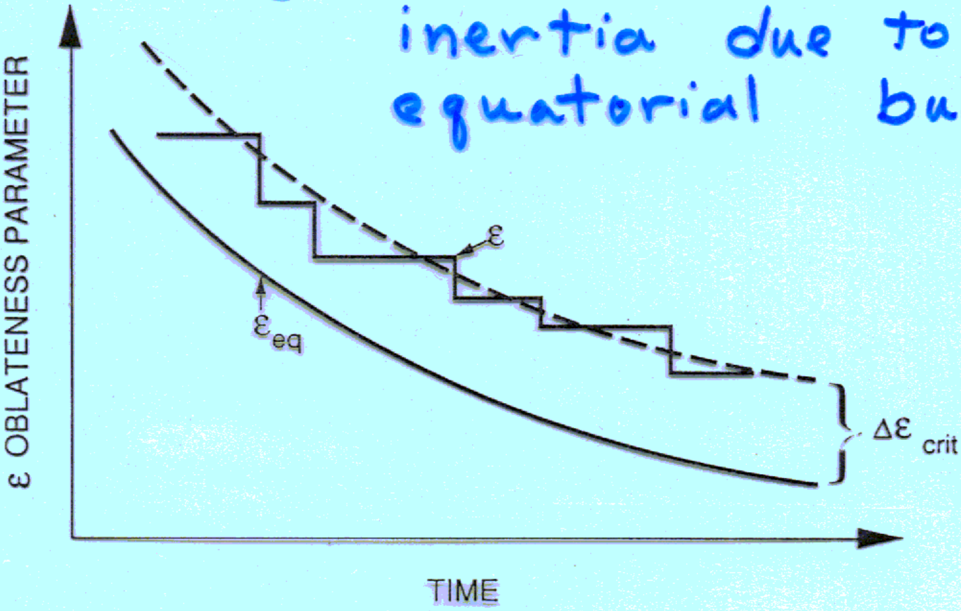
Conservation of angular momentum gives spin rate jumps: glitches

Star-quake Glitches



$$I = I_0 (1 + \epsilon)$$

ϵ = excess moment of inertia due to equatorial bulge



$$\frac{\Delta \Omega}{\Omega} = -\frac{\Delta I}{I} = -\Delta\epsilon$$

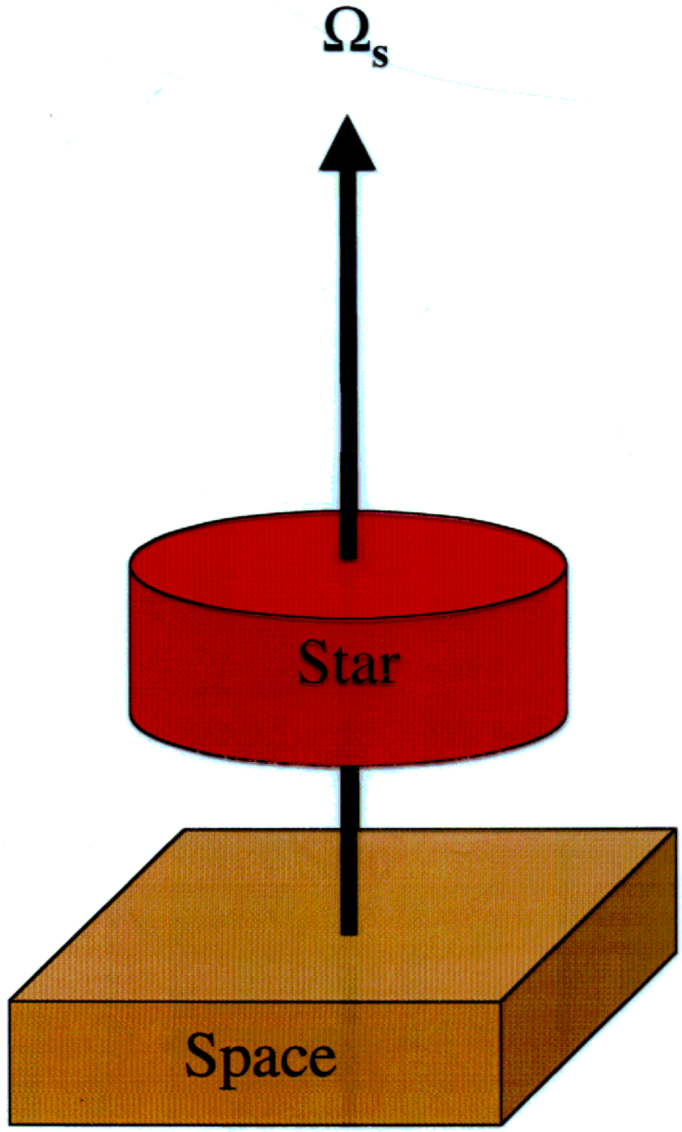
$$\langle \Delta \epsilon \rangle \sim t_{rep} \left(\frac{d\epsilon}{dt}\right)_{eq} \sim \frac{\dot{E}_{rot}}{E_{grav}} t_{rep}$$

for Vela pulsar:

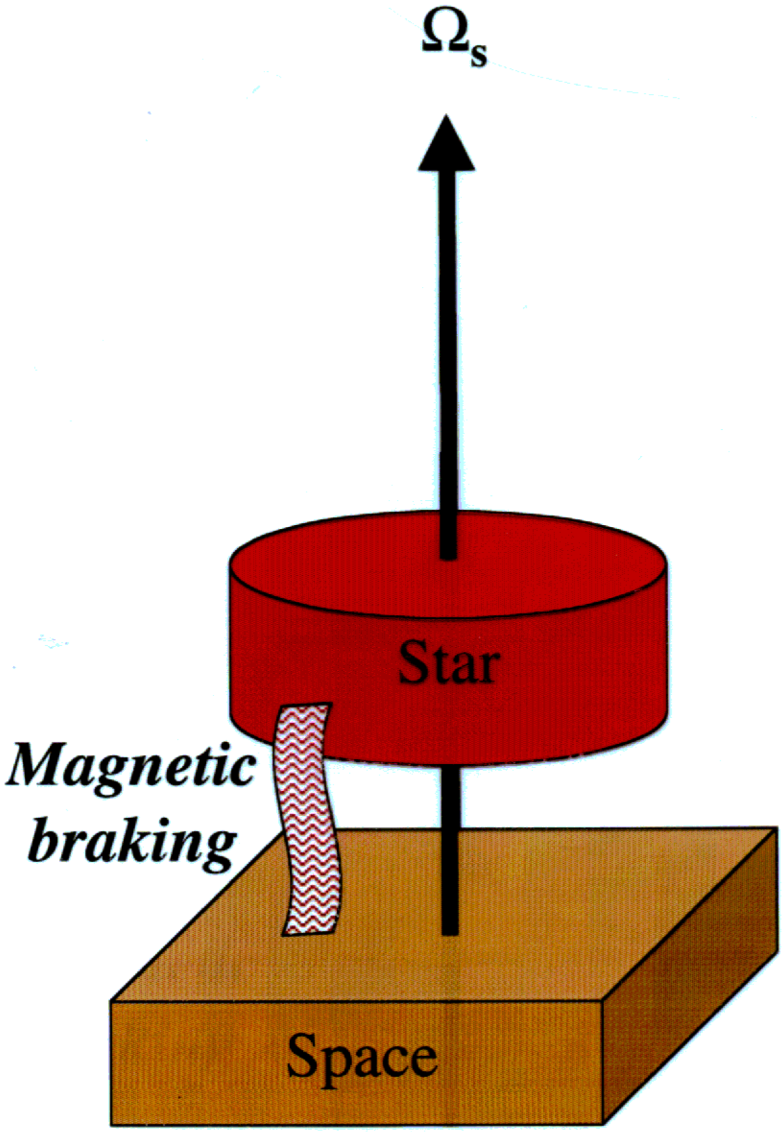
$$\langle \Delta \epsilon \rangle \sim 4 \times 10^{-9}$$

Observed $\quad \frac{\Delta \Omega}{\Omega} \sim 2 \times 10^{-6}$

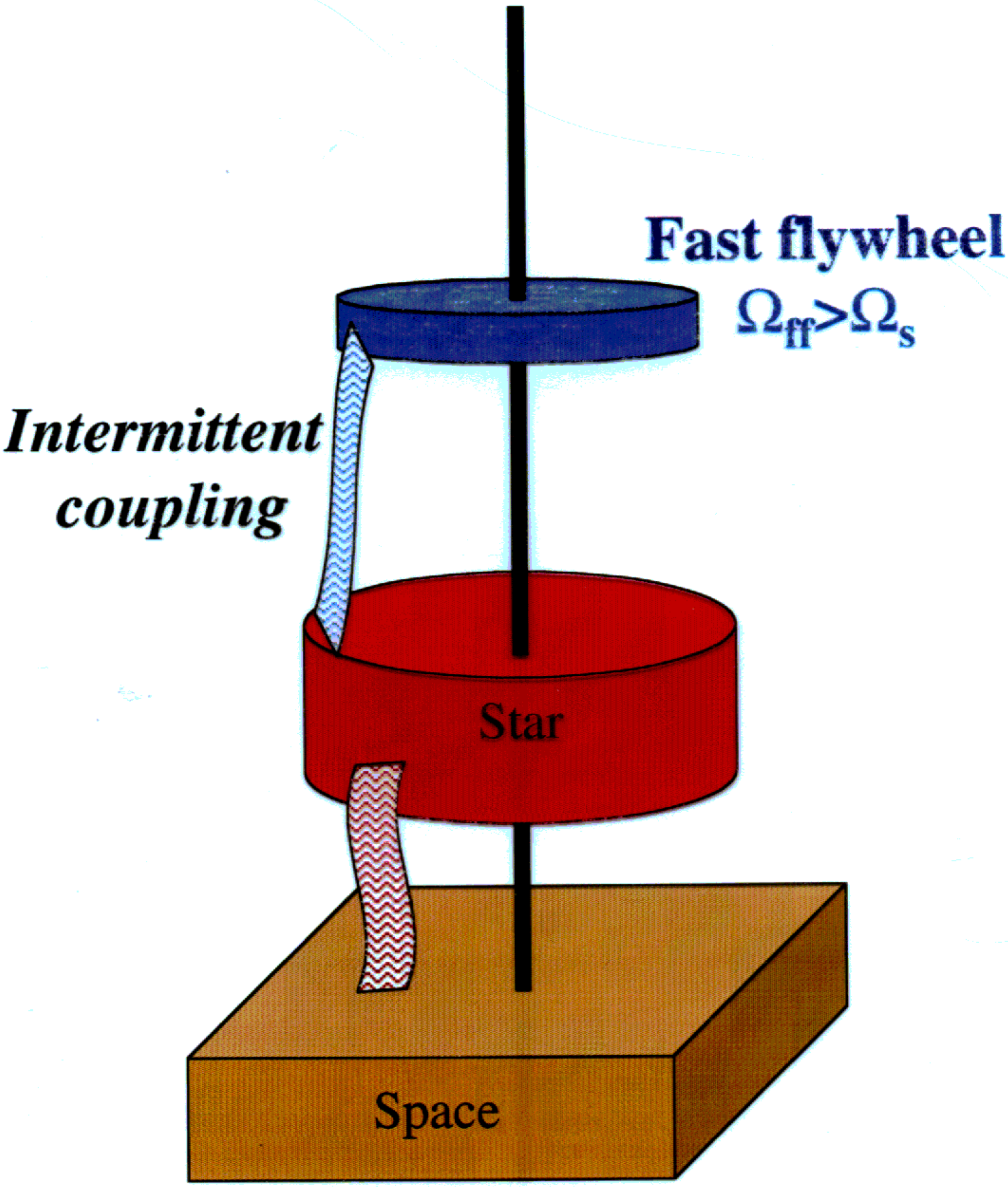
Freely Rotating Star



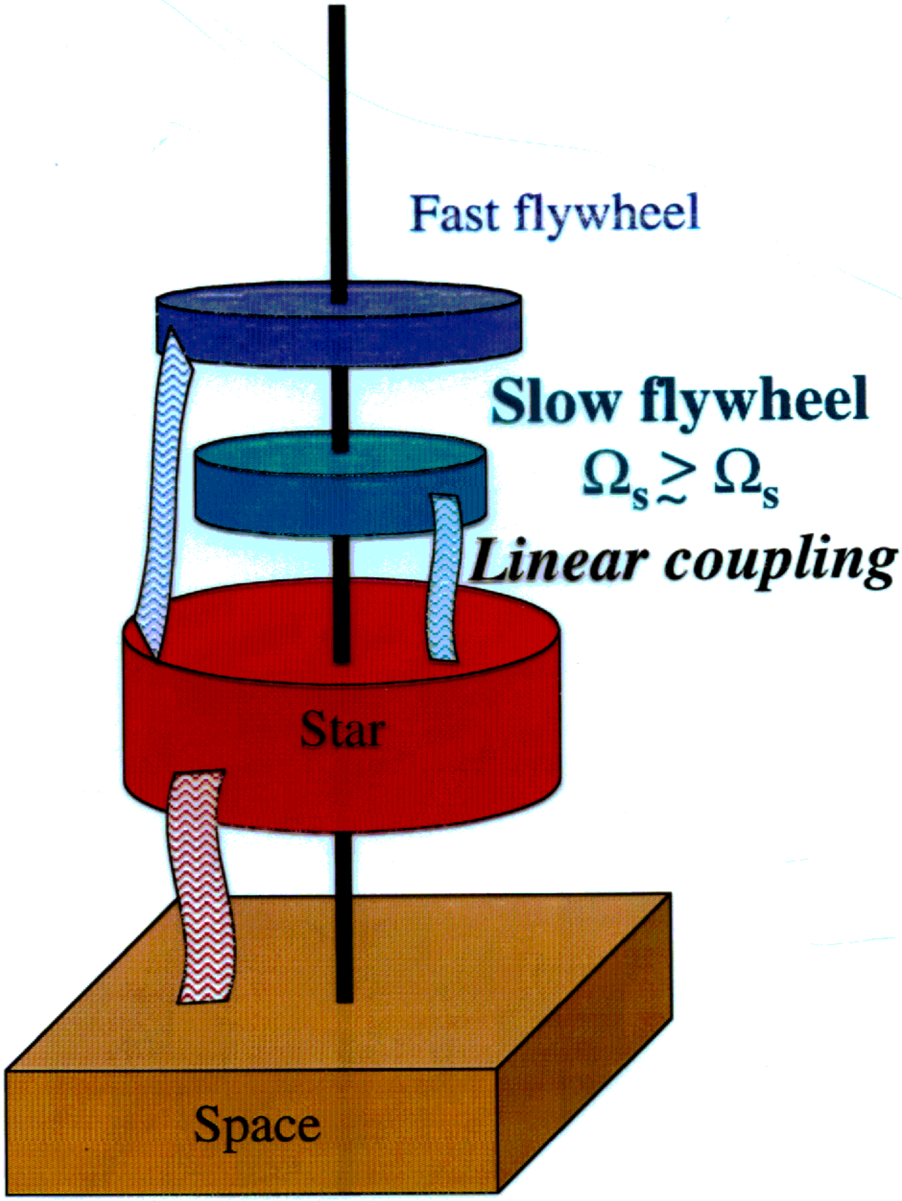
Steadily Slowing Star



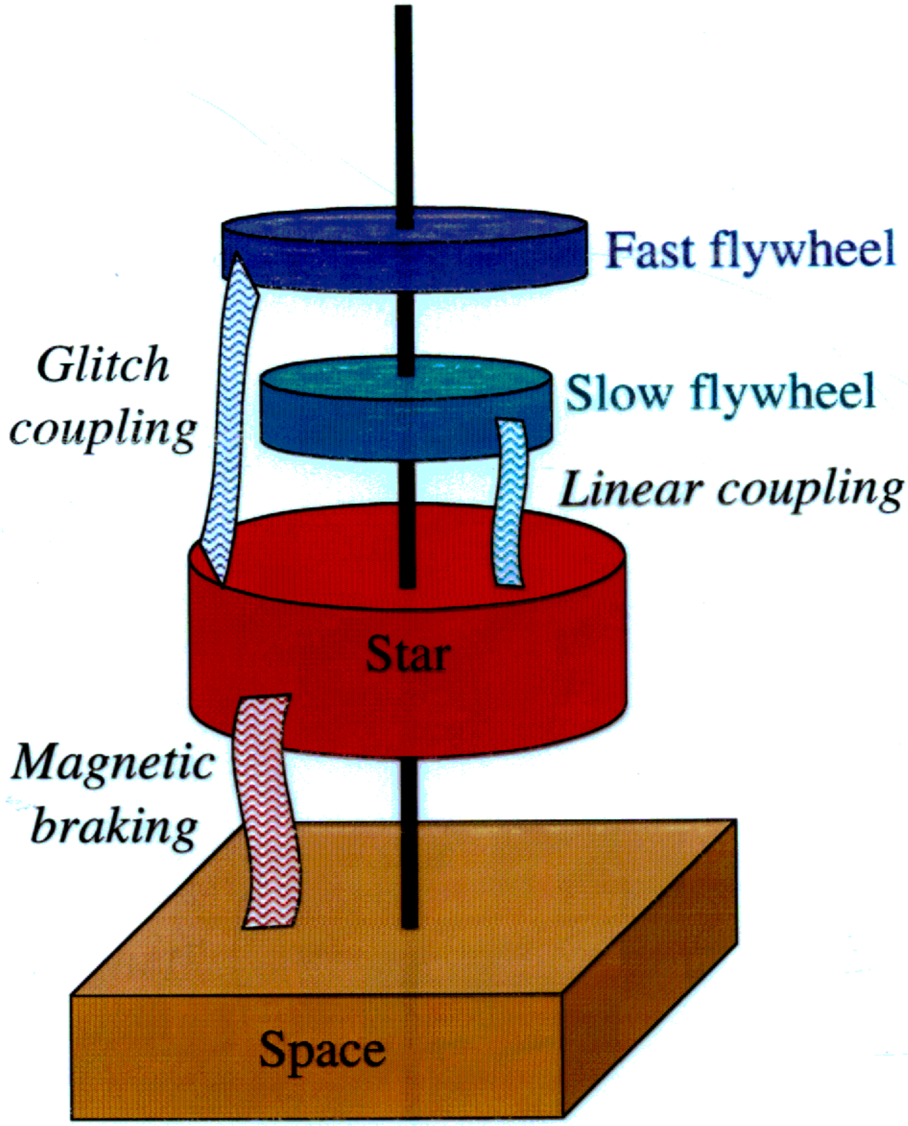
Star Experiencing Occasional Glitches



Star Exhibiting Partial Healing After Glitches

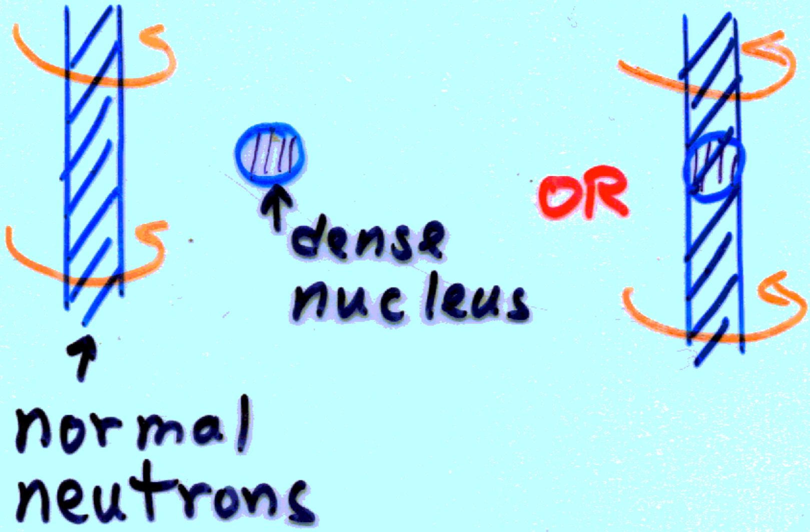


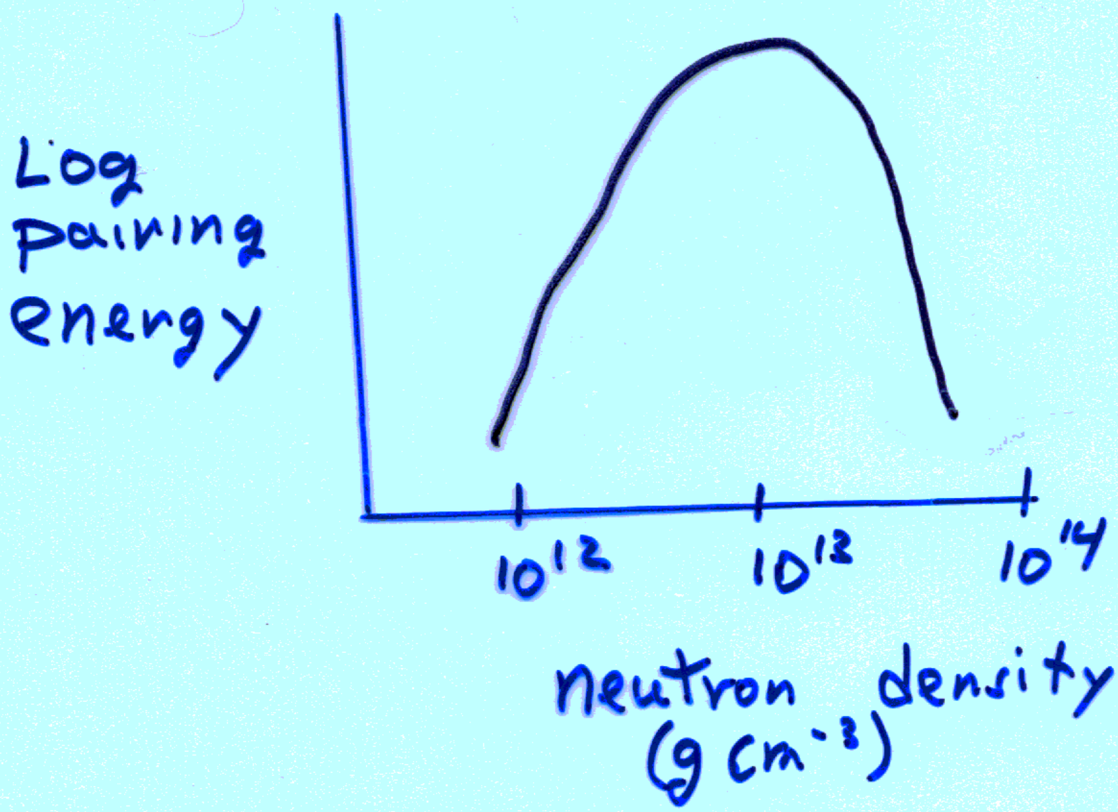
Minimal Dynamical Model For Neutron Star Dynamics



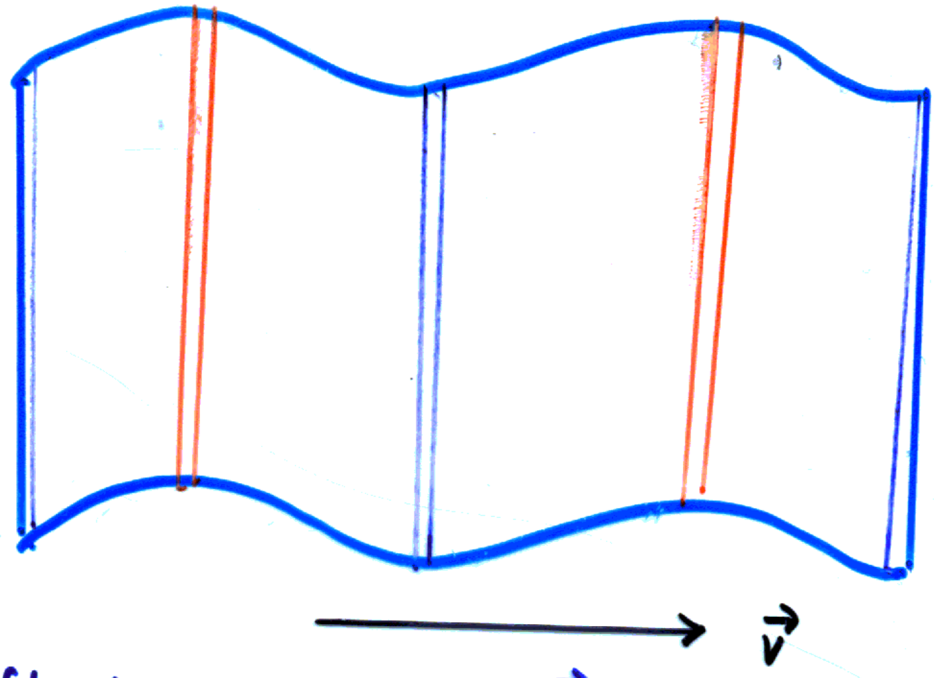
- **Persistent spin-down offsets may be steps in the magnitude of the magnetic braking torque**
- **Timing noise may be due to changes in the stellar moment of inertia**

Vortex Pinning

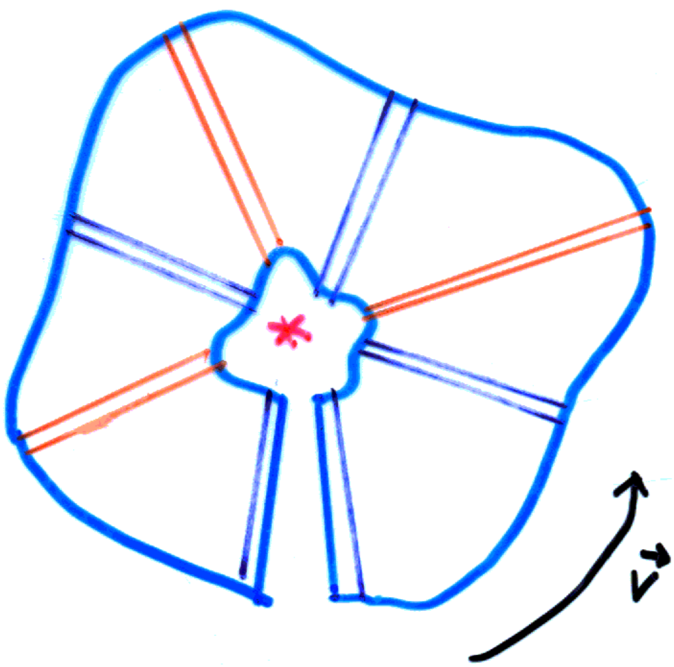




system wants to maximize matter near 10^{13} $g\ cm^{-3}$



superfluids have $\vec{\nabla} \times \vec{v} = 0$



Distribution of vortex lines $\Longleftrightarrow$ superfluid velocity field

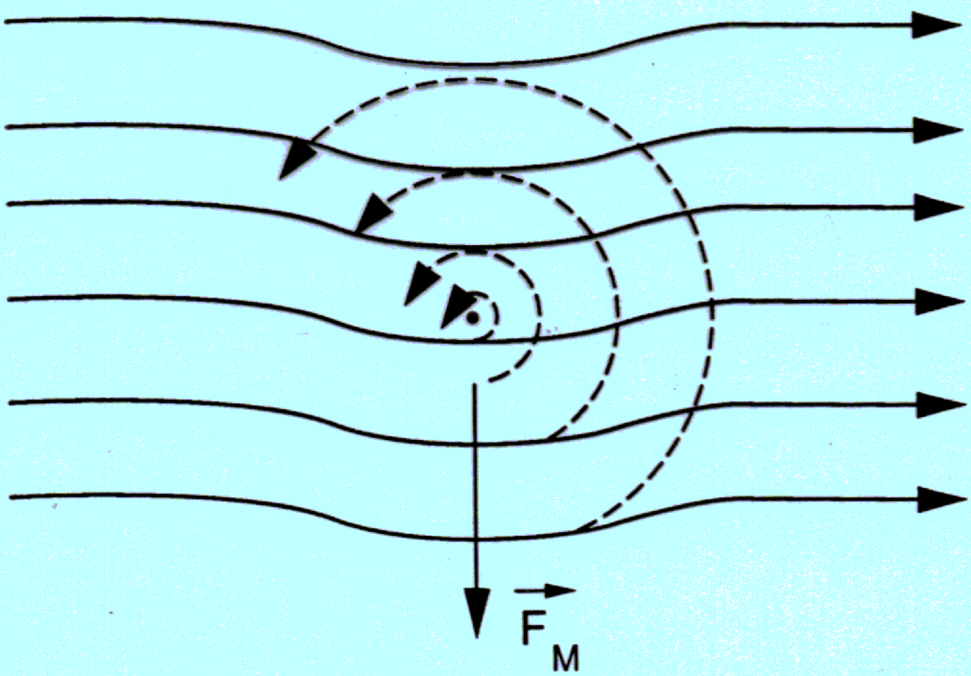
one determines the other

Magnus Force

Superfluid flow past a pinned vortex line creates a force perpendicular to the average superfluid velocity

Bernoulli's equation:

$P + \rho \; v^2/2 = \text{constant}$

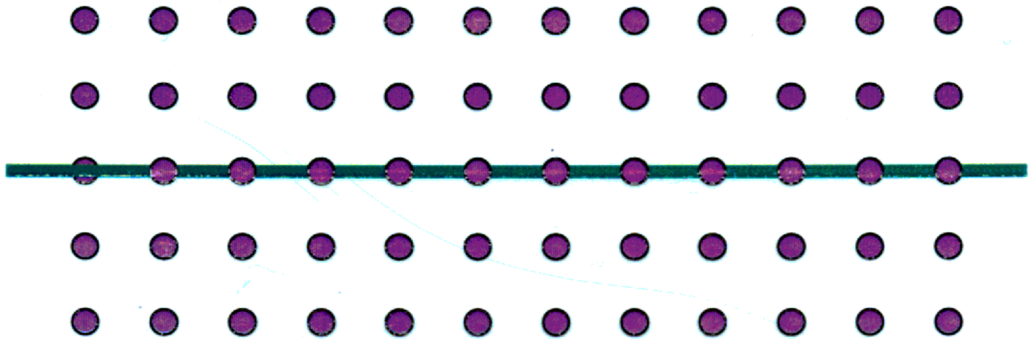


$\kappa = \pi\hbar/m_n = 2 \times 10^{-3} \;\; cm^2 s^{-1}$

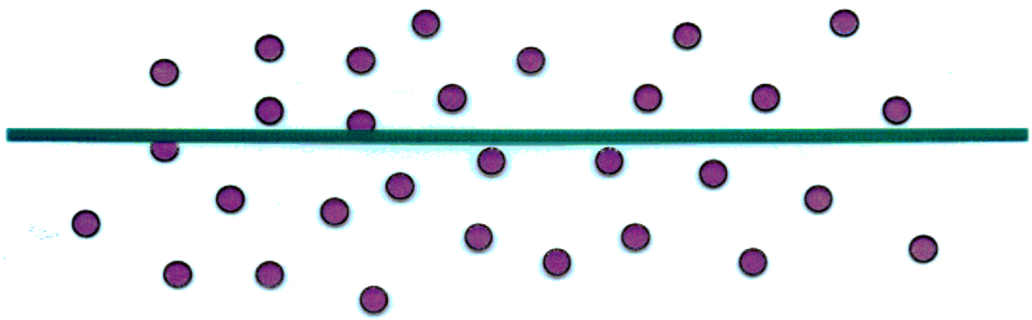
$F_{Magnus} = \rho_s \, \kappa \, (v_s - v_v)$

Vortex Pinning in a Glassy Crust

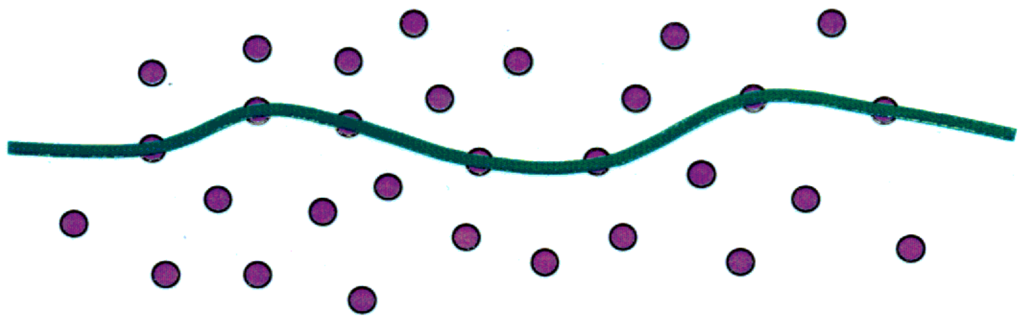
Crystal: $E_{pin,max} = U_0/a$ = binding energy/length



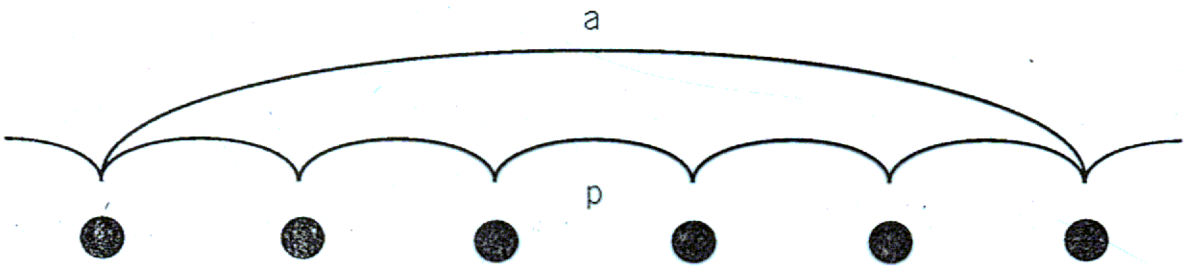
Stiff Vortex Line in Glass: $E_{pin} \approx 0$



Flexible Vortex Line in Glass:
$E_{pin} \approx U_0^2/(8Ta^2) \sim (r_N/a\tau)E_{pin,max}$
$\tau = 4r_N^2T/(3\ U_0 a)$ = "stiffness parameter"



A_L = Minimum energy barrier for unpinning a segment of length L



Unpinning rate:

$$R_L = \frac{\omega_L}{2\pi} \exp\left[-\frac{A_L}{KT}\right]$$

Vortex creep rate:

$$v_{cr} = \sum_L R_L \delta_L$$

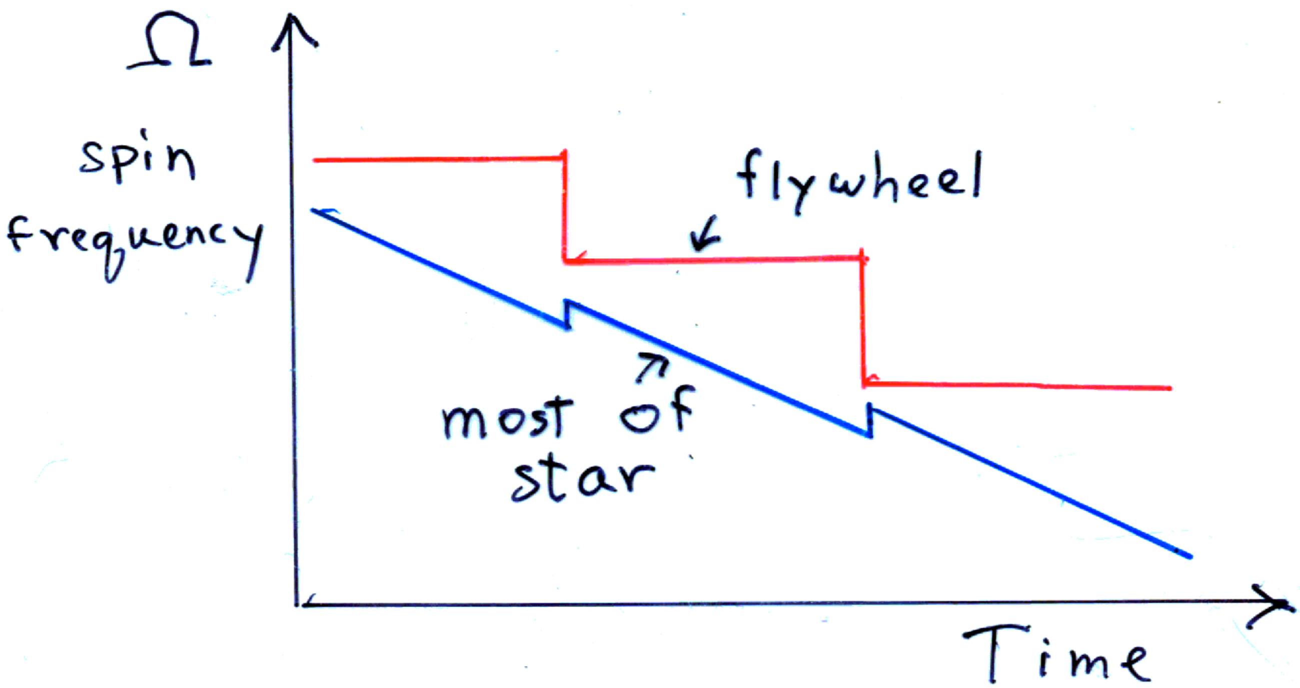
δ_L = Distance moved before repinning

Flywheel:

Most of the star slows steadily - Via magnetic radiation.

The flywheel is a small component of the star which retains the old rotation period.

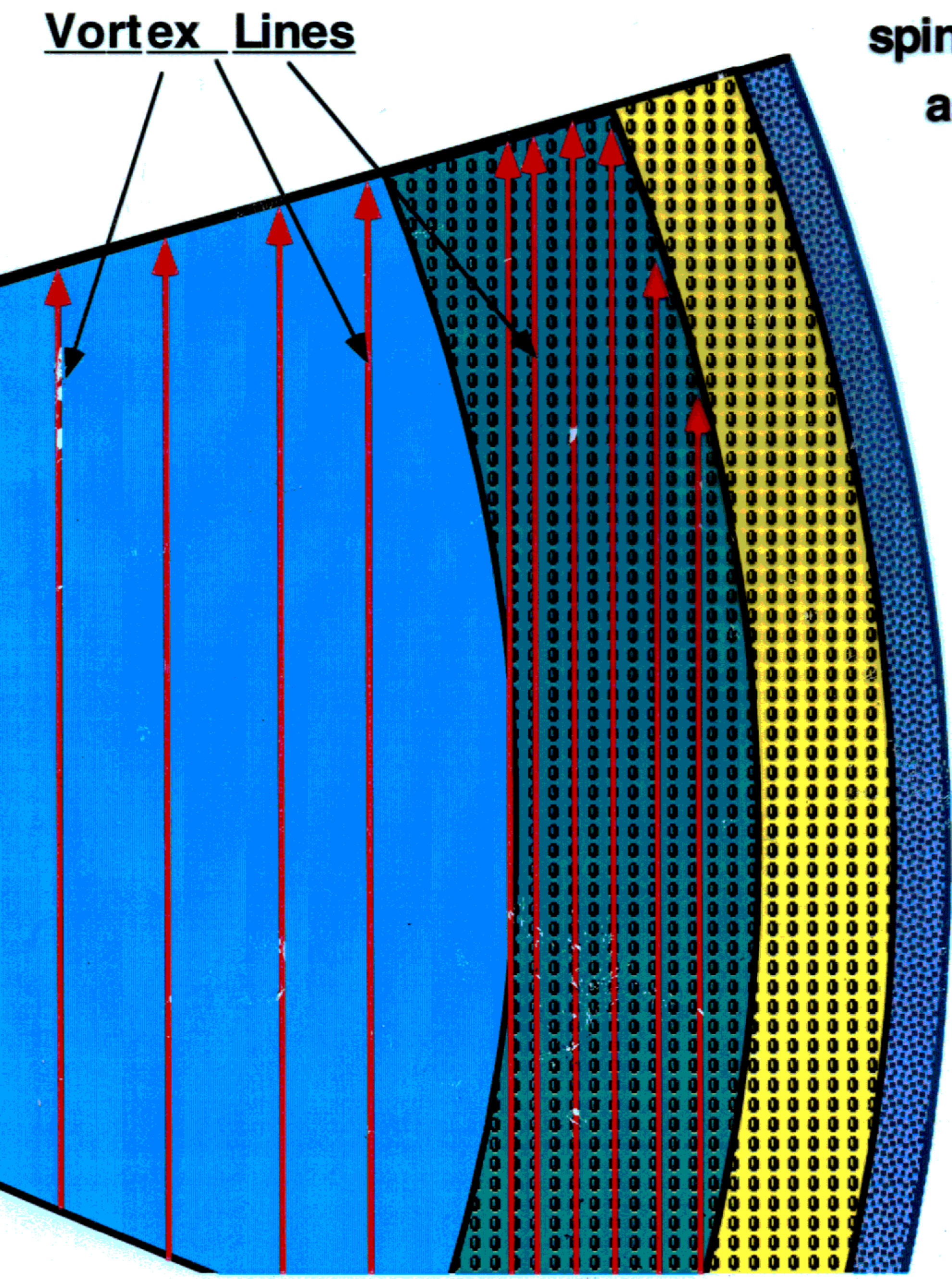
An instability (grit in the bearings) suddenly couples the flywheel to the rest of the star.

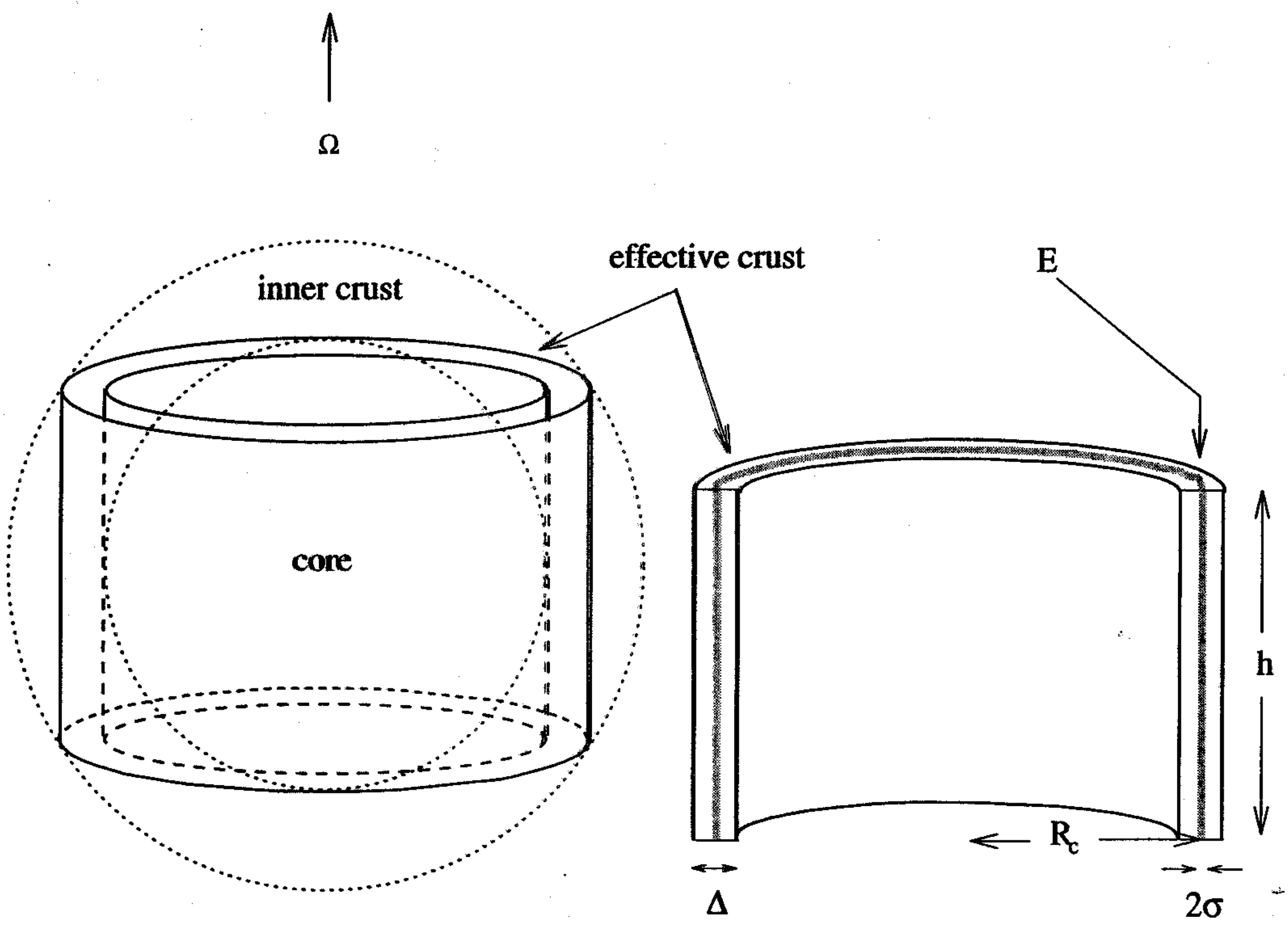


In a neutron star the flywheel = neutron superfluid in the inner crust (where proto are bound in nuclei)

Rotation of the neutron Superfluid in the Inner Crust

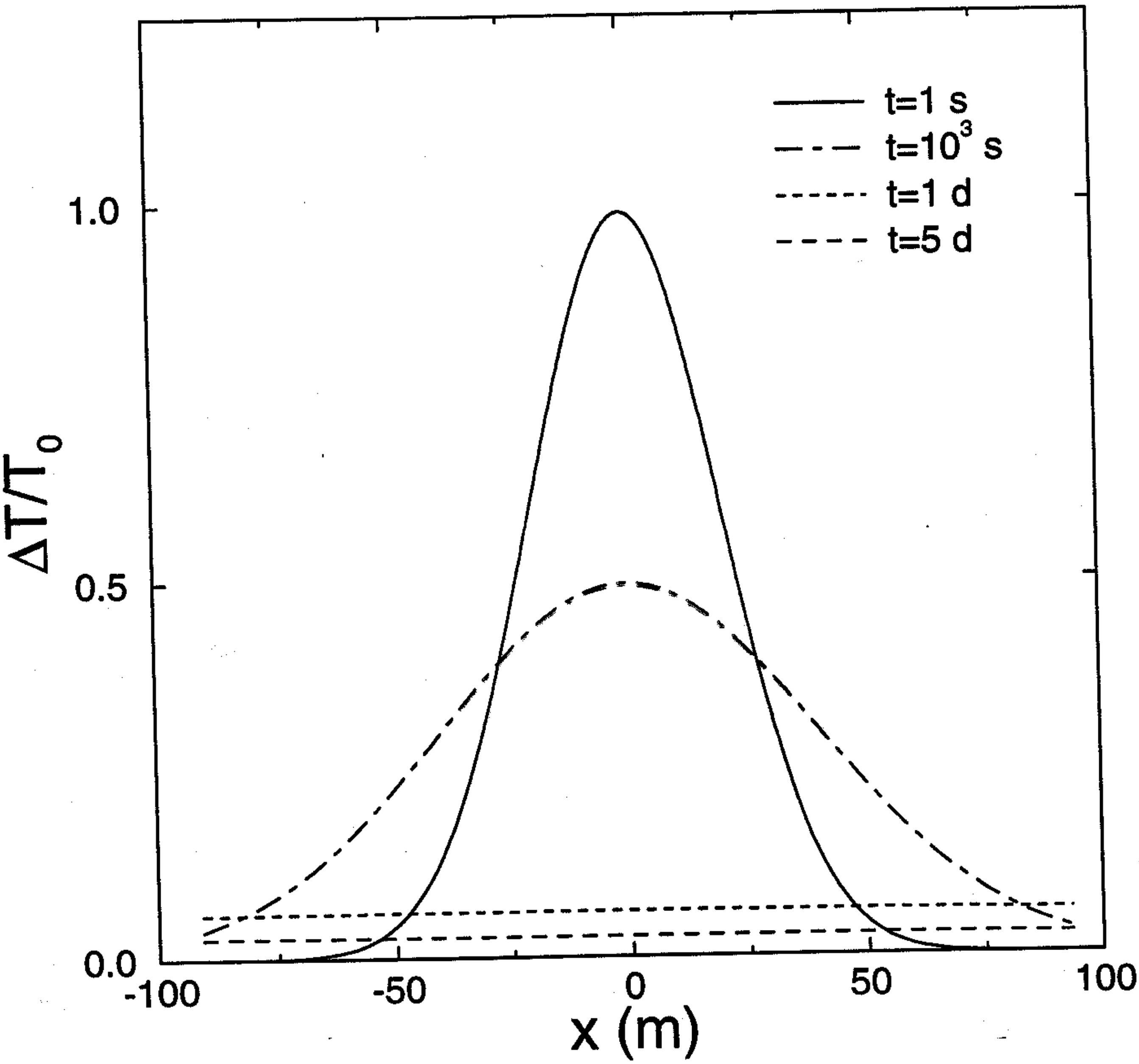
Pinning of vortex lines on nuclei in crystal lattice prevents superfluid from spinning as slowly as the crust

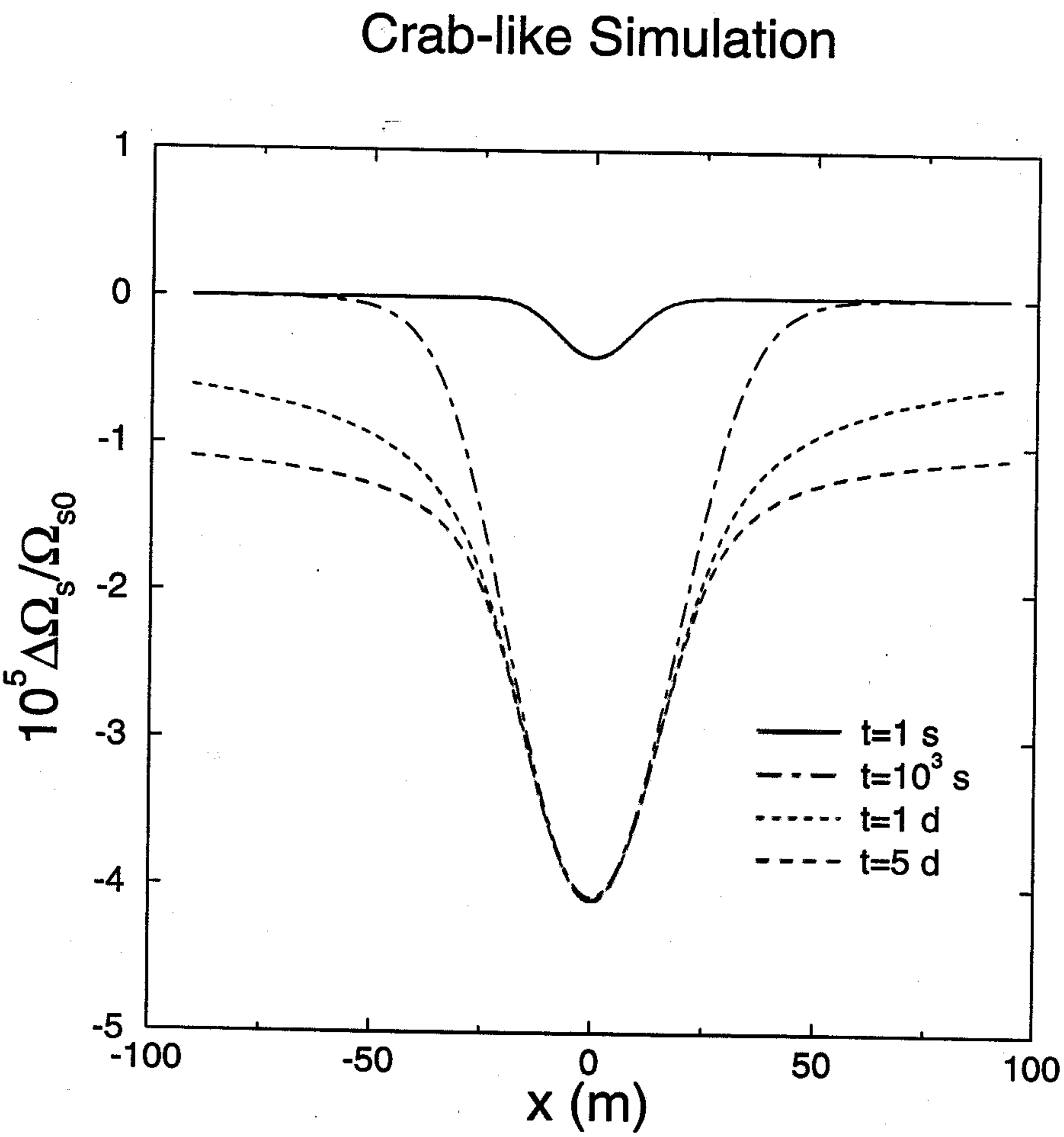




Ω
inner crust
core
effective crust
E
h
R_c
Δ
2σ

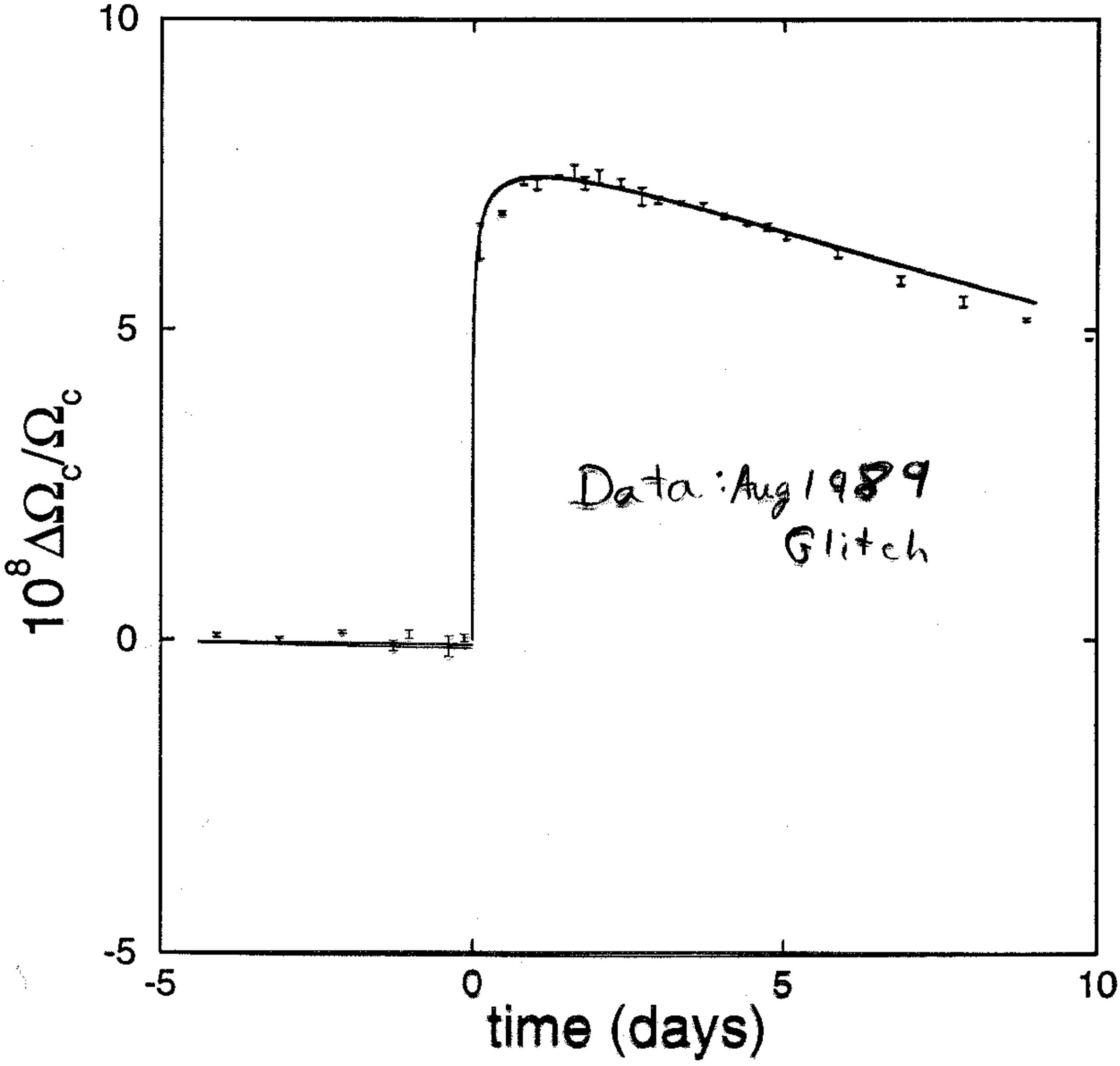
Crab-like Simulation





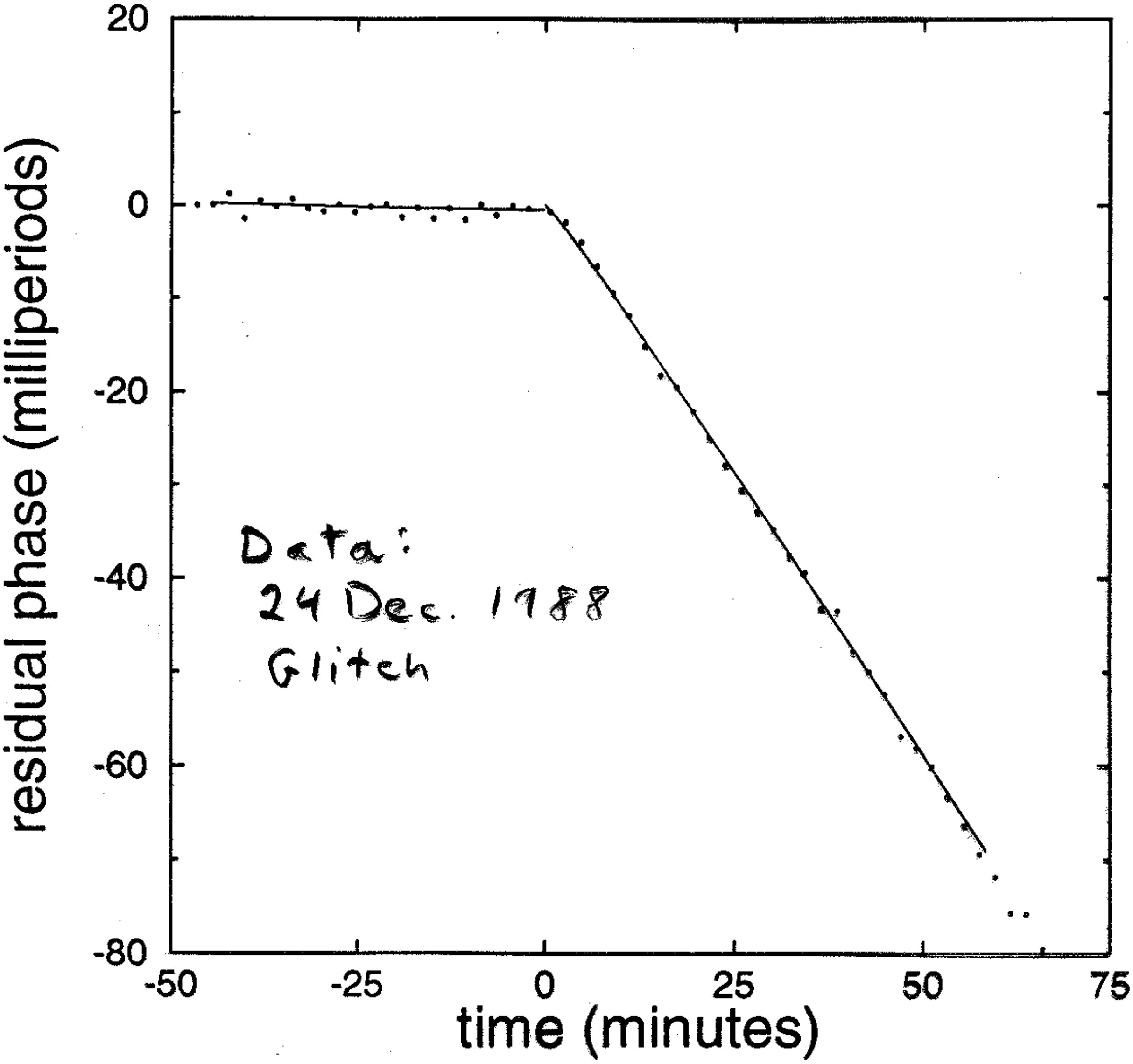
Crab-like Simulation
1
0
-1
-2
-3
-4
-5
-100
-50
0
50
100
$10^5 \Delta\Omega_s/\Omega_{s0}$
x (m)
t=1 s
$t=10^3$ s
t=1 d
t=5 d

Crab-like Simulation

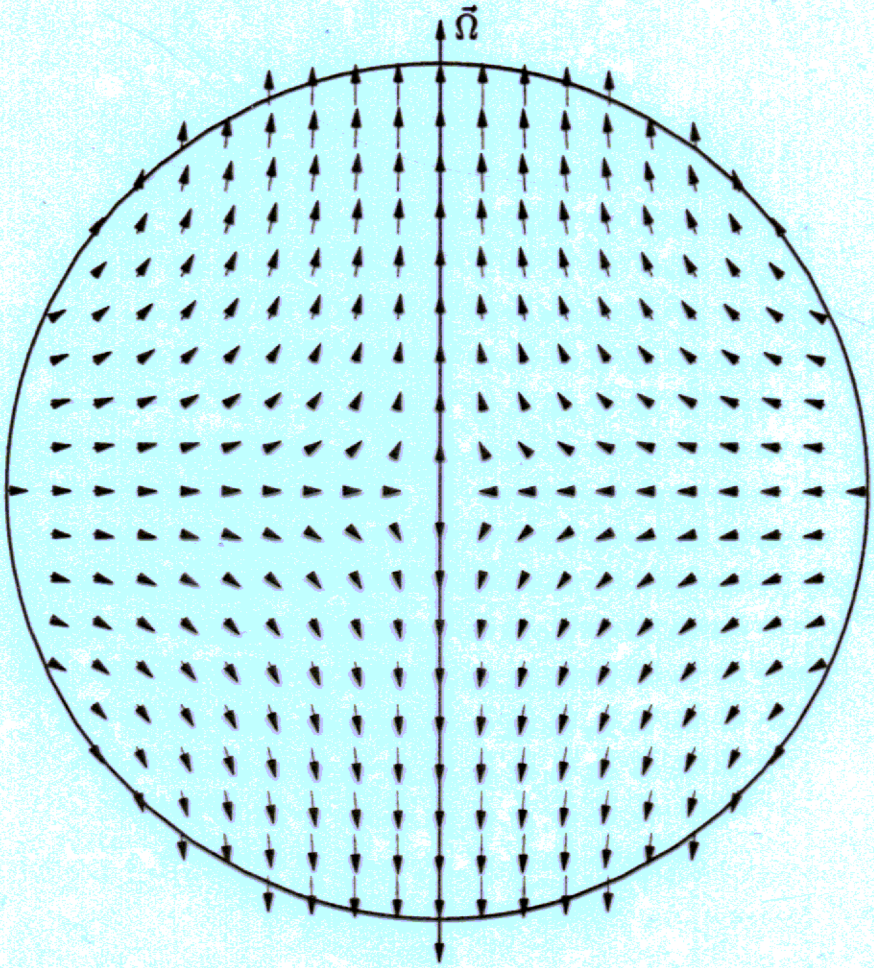


Link & Epstein, ApJ 457, 844 (1996)

Vela-like Simulation



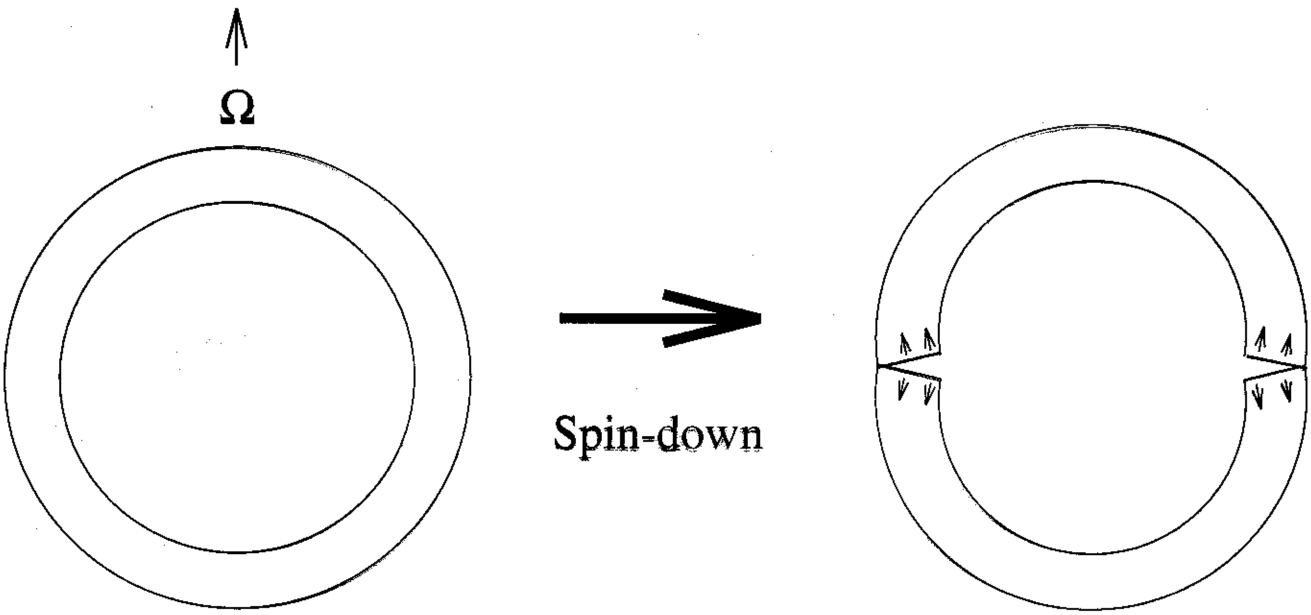
Material Displacements in a Slowing Neutron Star



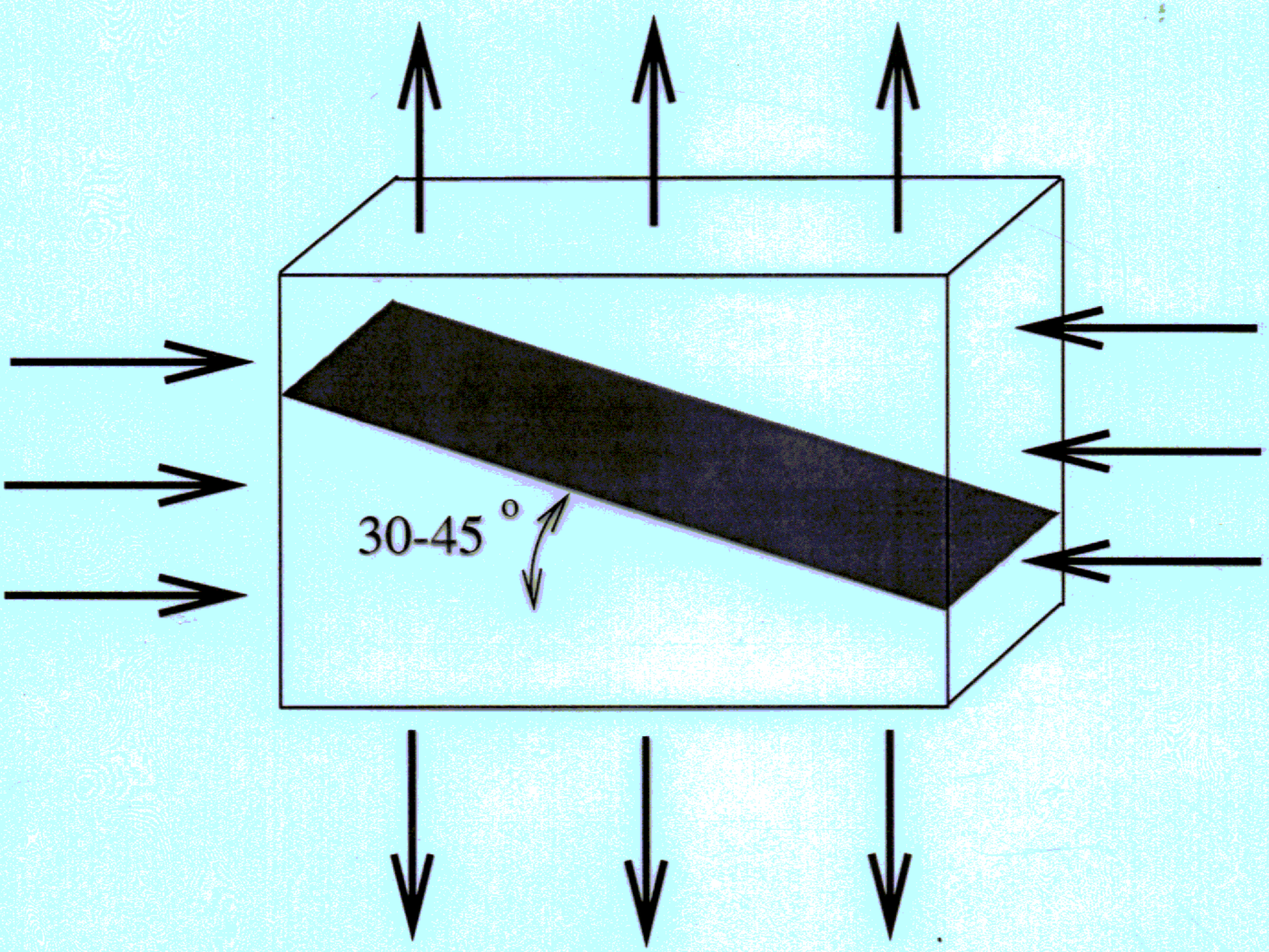
Equatorial circumference decreases as matter moves toward the rotational poles

WHAT DOES A STARQUAKE LOOK LIKE?

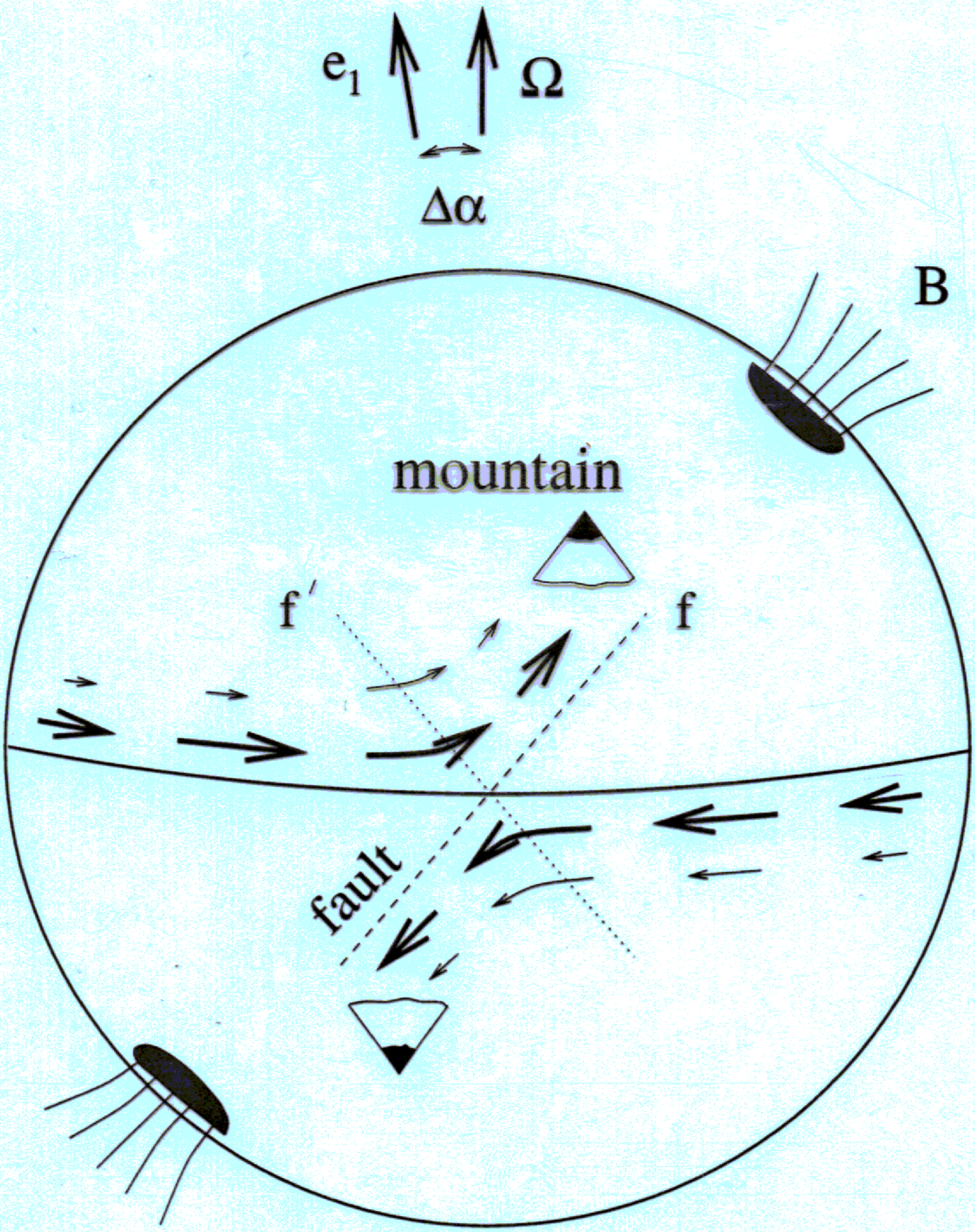
If internal pressure were negligible...



Compression-induced Fracturing



Building Mountains on Neutron Stars

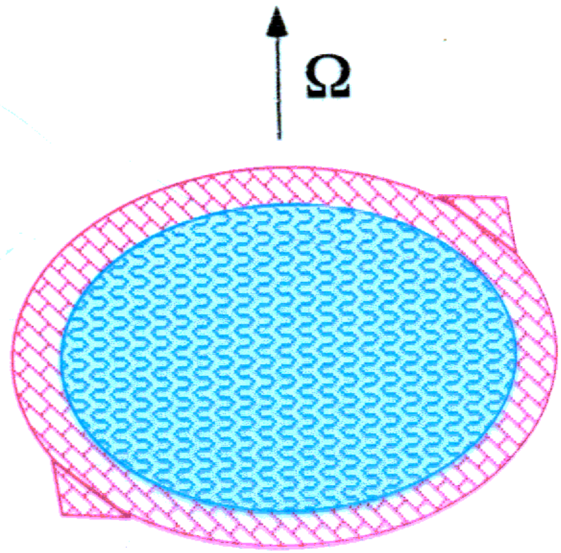


How starquakes can increase the spin-down torque on a neutron star

- The slowing star become more spherical
  - The equator shrinks
  - Matter is azimuthally compressed
- Faulting is most likely at the equator
  - The magnetic field favors some faults
  - Matter moves toward the magnetic poles
- Star precesses (J and Ω misaligned)
  - Precession quickly damps
  - Magnetic poles move toward the rotational equator
- Magnetic-dipole torque increases

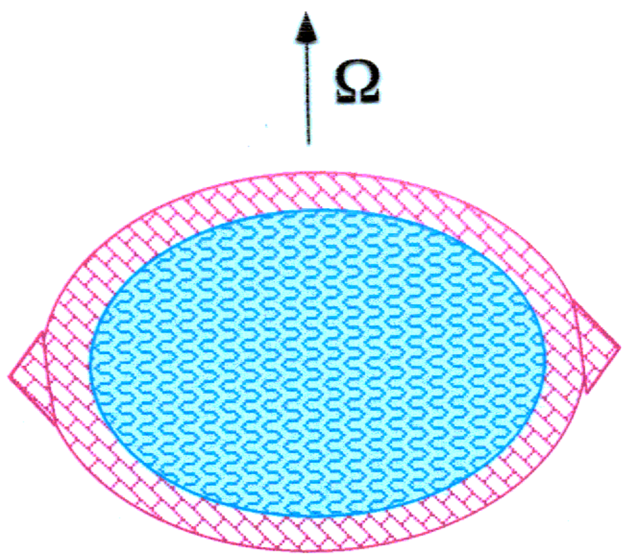
$$d\Omega/dt \sim -\Omega^3 B^2 \sin^2\alpha$$

Axes Realignment

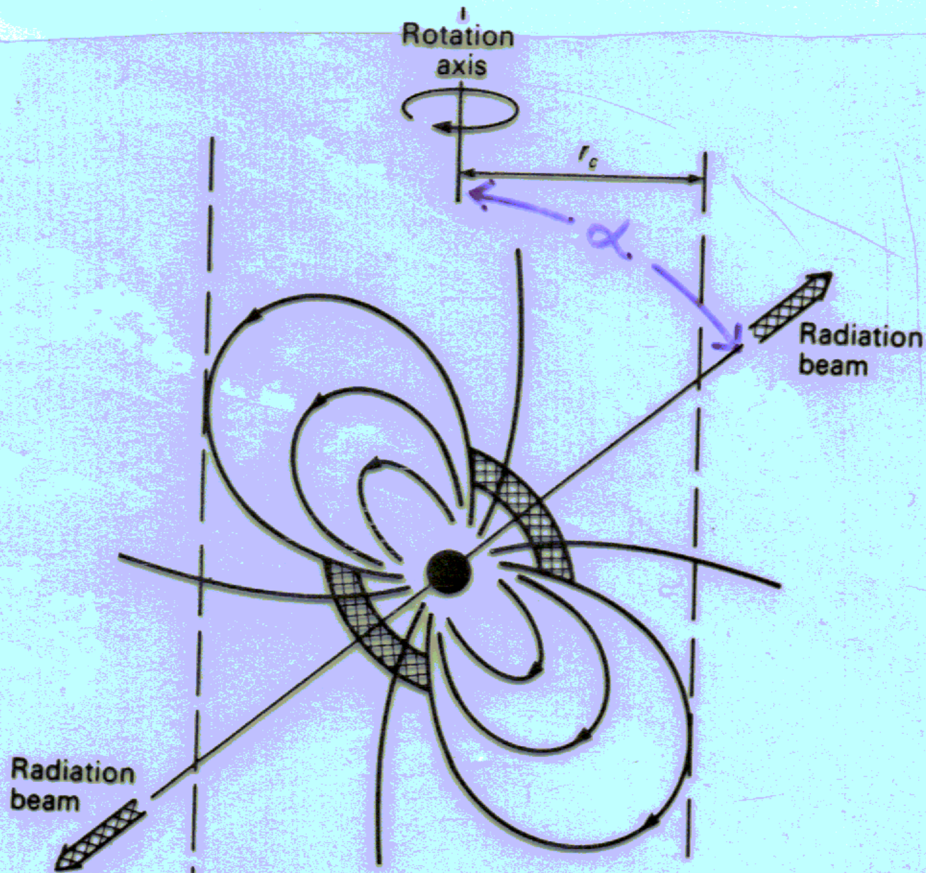


Rotational energy = $J^2/2I_{perp}$

If the crust were "plastic" the mountains would migrate to the rotational equator



Torque Change



Spin rate slows by magnetic dipole radiation

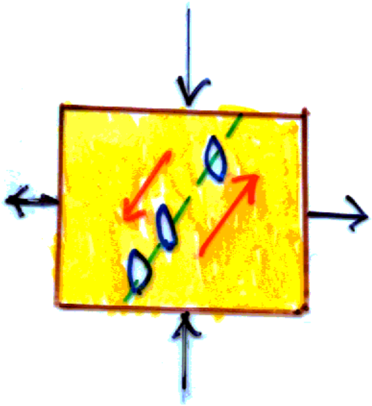
$$d\Omega/dt \sim -\Omega^3 B^2 \sin^2\alpha$$

or related process

Critical Question

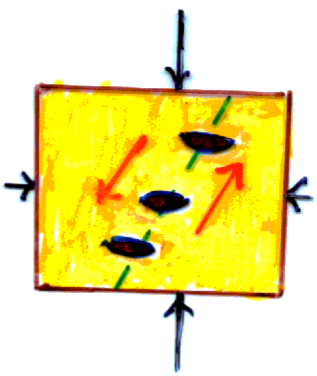
Can neutron-star crusts truly crack?

Low pressure:
micro cracks = cavities



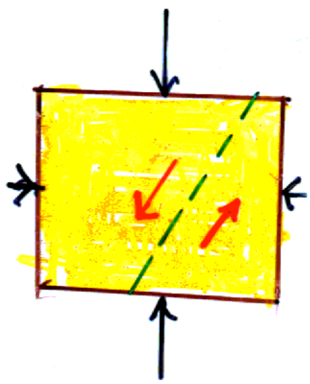
Brittle failure

High-pressure phase transition:
anticracks = dense seeds



Anticrack failure

High pressure sliding instability



Crackless failure

Brittle materials become ductile when subjected to high pressures

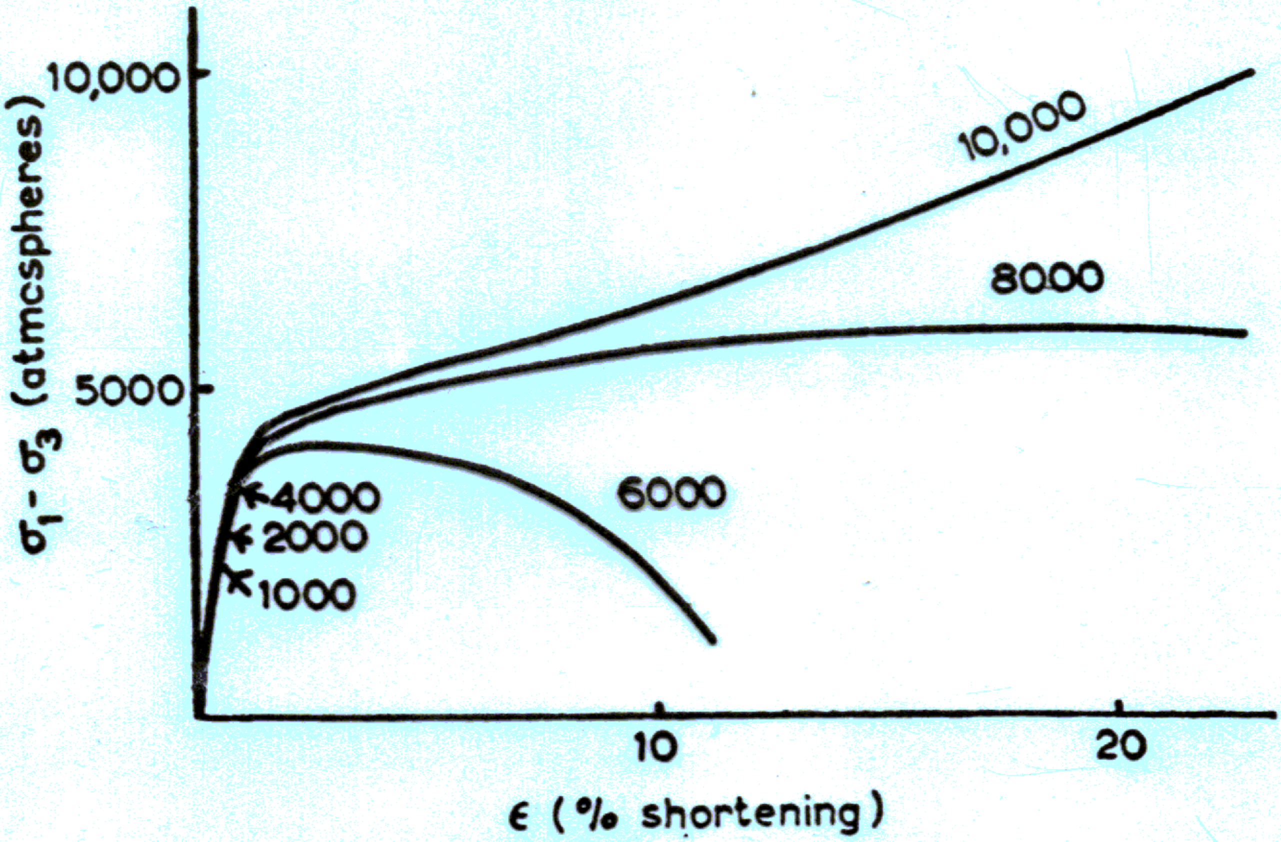


FIG. 20