The translational mode of the inner core, the so-called Slichter mode: amplitude and associate phase transformations

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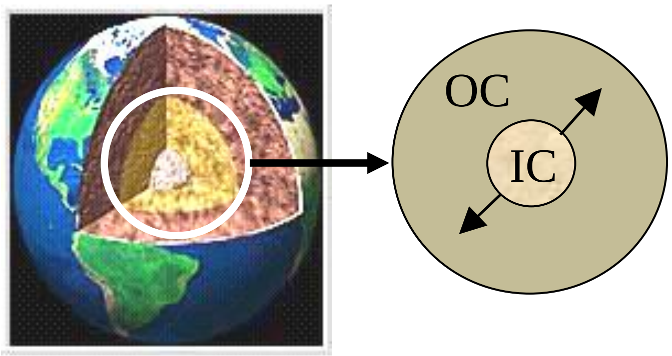
The « Slichter » mode $_1S_1$



<u>Translation of the inner core in the liquid outer core</u>

- period between 4h - 6h for realistic Earth models (e.g. PREM: 5.42 h) (Rieutord 2002, Rogister 2003);

- <u>perturbs surface gravity</u>: inertial 3% + free-air 96% + potential perturbation 1% of the total effect (Dahlen and Tromp, 1998)

Information on the viscosity and density jump at the ICB (Archimedean feedback)

<u>Impacts in :</u>

- seismology,
- geochemistry,
- geodynamic,
- geomagnetism.

[Slichter 1961; Smith 1976]

The « Slichter » mode ${}_1S_1$: A quest…

At Slichter frequency (~ 5 h) SGs are instruments with the lowest noise levels
→ Search for ${}_1S_1$ signal in SG time-varying gravity data from the GGP network

Controversial detection:
Smylie (1992), Courtier et al. (2000), Pagiatakis et al. (2007)

Rieutord (2000): such an observation incompatible with theory

No detection:
Hinderer et al. (1995), Jensen et al. (1995), Rosat et al. (2003, 2006, 2007, 2008), Guo et al. (2006, 2007) , Abd El-Gelil and Pagiatakis (2009), Ding and Shen (2013)

Combination of more and less noisy SG data

What is the expected Slichter mode surface amplitude?

Depends on the excitation process and damping mechanism

The « Slichter » mode ${}_1S_1$: Damping

<u>seismic anelasticity</u>:
Crossley et al. (1991) → Q ~ 5000

<u>outer-core viscosity:</u>
Mathews and Guo (2005) → Q ~ 5000

<u>Magnetic damping</u>:
Buffett and Goertz (1995) → $2200 < Q < 5.8\ 10^5$

} $Q \geq 2000$

What excitation processes?

${}_1S_1$: Which excitation mechanisms?

- Smith (1976);
- Crossley (1987; 1992);
- Rosat (2007);

} Seismic excitation

- Greff-Lefftz and Legros (2007);

} Pressure flow at core boundaries

- Rosat and Rogister (2012);

} Pressure flow at core boundaries, meteoroid impact, surface pressure load

- Rosat et al. (2014).

} ECMWF and NCEP/CFSR (meteorological center data) surface atmospheric pressure load

${}_1S_1$: Seismic excitation amplitude

$$\mathrm{A_x(x)} = \left(\frac{2l+1}{4\pi}\right) D(r,\Theta,\Phi)\mathrm{A}(\Theta,\Phi)$$

[Dahlen & Tromp, 1998]

$$\mathrm{A}(\Theta,\Phi) = A_0\cos\Theta + A_1\sin\Theta\cos\Phi + B_1\sin\Theta\sin\Phi$$

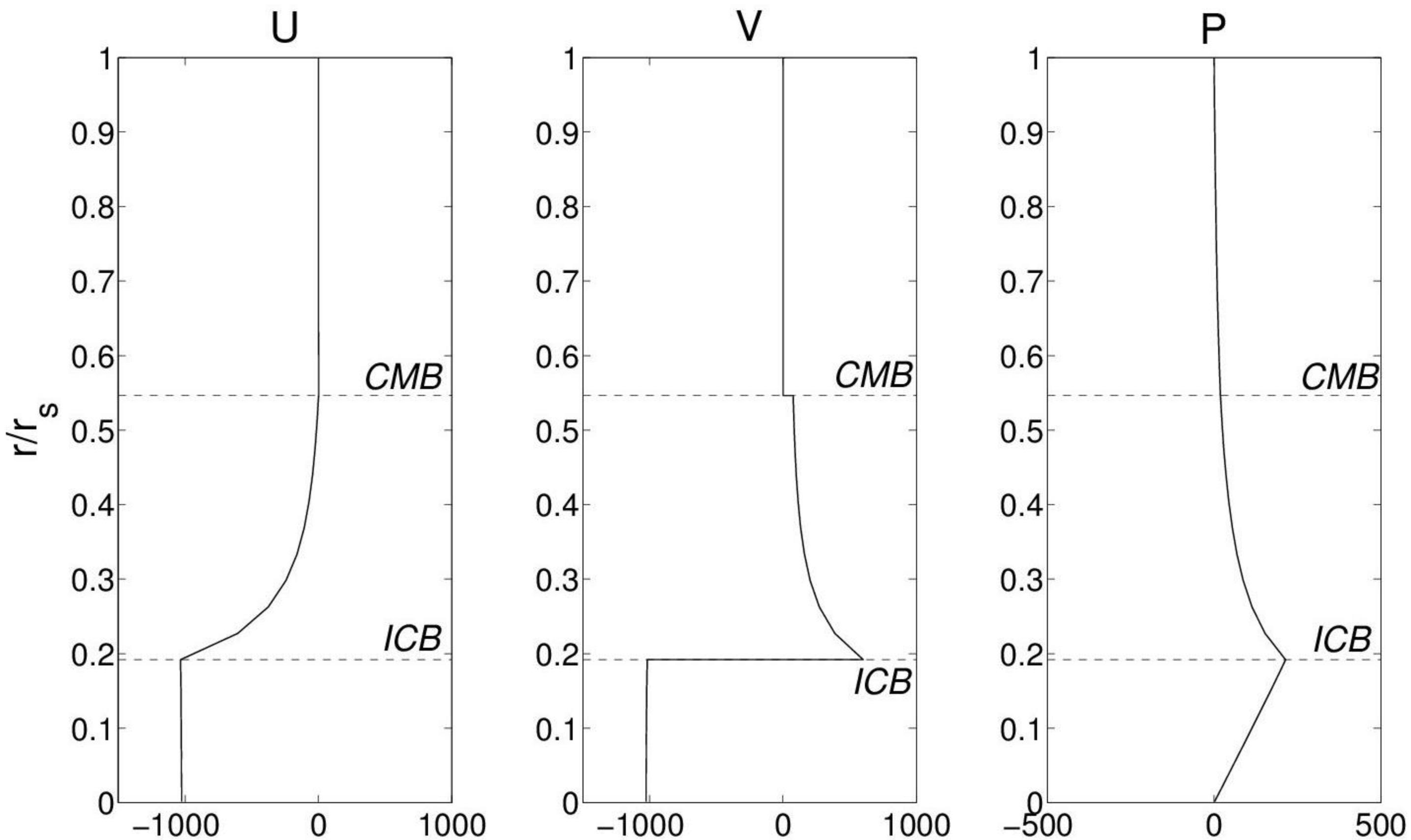
$$\mathrm{A_0} = M_{rr}\dot{U}_s + \left(M_{\theta\theta} + M_{\phi\phi}\right) r_s^{-1}\left(U_s - \frac{1}{2}kV_s\right),$$

$$\mathrm{A_1} = k^{-1}M_{r\theta}\left(\dot{V}_s - r_s^{-1}V_s + kr_s^{-1}U_s\right),$$

$$\mathrm{B_1} = k^{-1}M_{r\phi}\left(\dot{V}_s - r_s^{-1}V_s + kr_s^{-1}U_s\right).$$

The effect of the source depth is represented by $1/r_s$, while the seismic moment *M* directly scales the excitation amplitude.

${}_1S_1$: Eigenfunctions



[Rosat & Rogister 2012]

→ small excitation amplitude expected

Seismic excitation amplitude

Event	Chile 1	Chile 2	Chile 1+2	Alaska	Bolivia	Peru	**Andaman-Sumatra**	Maule-Chile	Tohoku
Date	1960	1960	1960	1964	1994	2001	**2004**	2010	2011
M_w	9.5	9.6	9.8	9.2	8.2	8.4	**9.3**[1]	8.8	9.1
Reference for the source model	*Kanamori and Cipar (1974)*			*Kanamori (1970)*	*Global CMT**				
	Surface gravity effect in **nGal** (= 10^{-2} nm/s^2)								
Smith (1976)	0.94	1.2	-	0.58	-	-	-		
Crossley (1992)	0.724	0.835	**1.52**	0.34	0.02[2]	-	-		
Rosat (2007)	0.656	0.853	**1.51**	0.19	0.007	0.010	**0.29**	0.095	0.145

[1] Stein and Okal (2005)
[2] personal communication

(⇔surface displ. ~1 µm)

Vertical dip-slip $M_W > 9.7 \rightarrow A > 1$ nGal

[Rosat 2007]

Collision with a meteoroid (seismic impact)

Location	Date	Diameter (m)	Density (kg/m^3)	M_w	Δg (nm/s^2)
Ries Crater Germany	15.1 ± 0.1 My BP	1500	2700 (rock)	7.4	$3.9\ 10^{-6}$
Rochechouart France	214 ± 8 My BP	1500	3350 (stony-iron)	7.5	$4.9\ 10^{-6}$
Chesapeake Bay USA	35.5 ± 0.3 My BP	2300	2700 (rock)	7.8	$1.4\ 10^{-5}$
Chicxulub Mexico	**65 ± 0.05 My BP**	**17500**	**2700 (rock)**	**9.6**	$\mathbf{6.7\ 10^{-3}}$

Based on simplified computations of **Collins et al. (2005)**, *Meteoritics & Planetary Science*.

[Rosat & Rogister 2012]

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Seismic efficiency
$10^{-5} < k_s < 10^{-3}$
(Schultz and Gault , 1975)

Here $k_s = 10^{-4}$

BUT if $k_s = 10^{-3}$
M_w = 10.2
= $6.7\ 10^{-2}$ nm/s²

Based on simplified computations of **Collins et al. (2005)**, *Meteoritics & Planetary Science*.

[Rosat & Rogister 2012]

Surface atmospheric load

$$\Delta g(r,\theta,\phi;t) = \frac{r_s^2 U(r)}{i\nu}[U(r_s)g_0 + P(r_s)]$$
$$[\int_{-\infty}^{t} e^{i\nu t'}(\sigma_{10}(t')\cos\theta + \sigma_{11}^c(t')\sin\theta\cos\phi + \sigma_{11}^s(t')\sin\theta\sin\phi)dt']$$
$$[-\omega^2 U(r_s) + \frac{2}{r_s} g_0 U(r_s) + \frac{2}{r_s} P(r_s)].$$

Degree-one surface load (from international meteorological center)

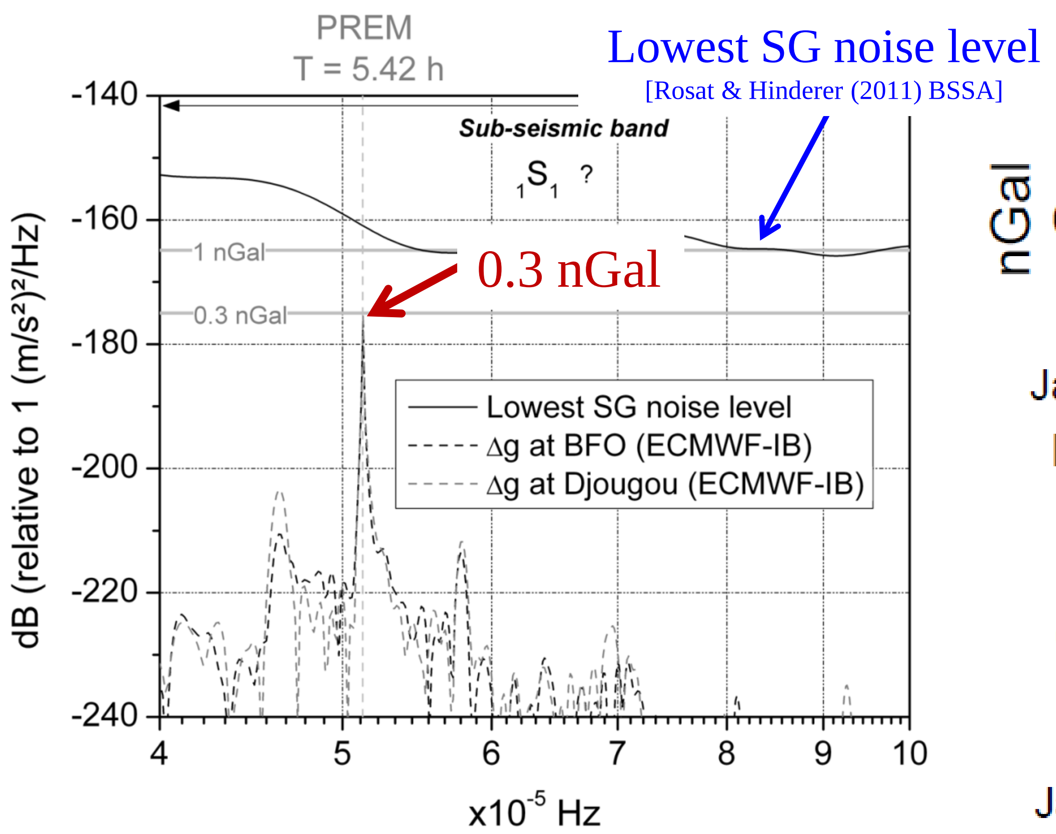
inertial — free-air — potential

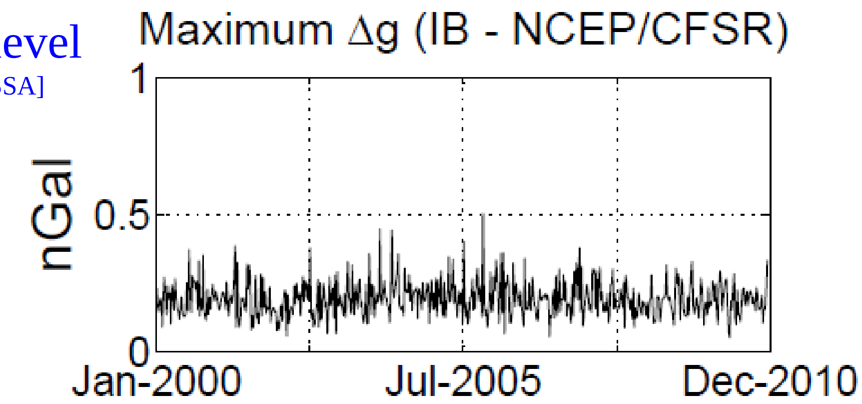
August 2008: hourly ECMWF (European Centre for Medium-Range Weather Forecasts) data available in the frame of the CONT08 intensive VLBI measurements (usually 3 h temporal resolution)

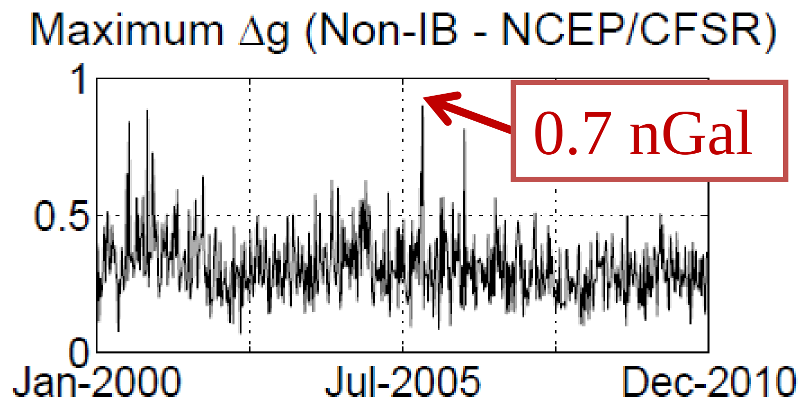
[Rosat et al. (2014) PEPI]

Surface atmospheric load

ECMWF and NCEP/CFSR







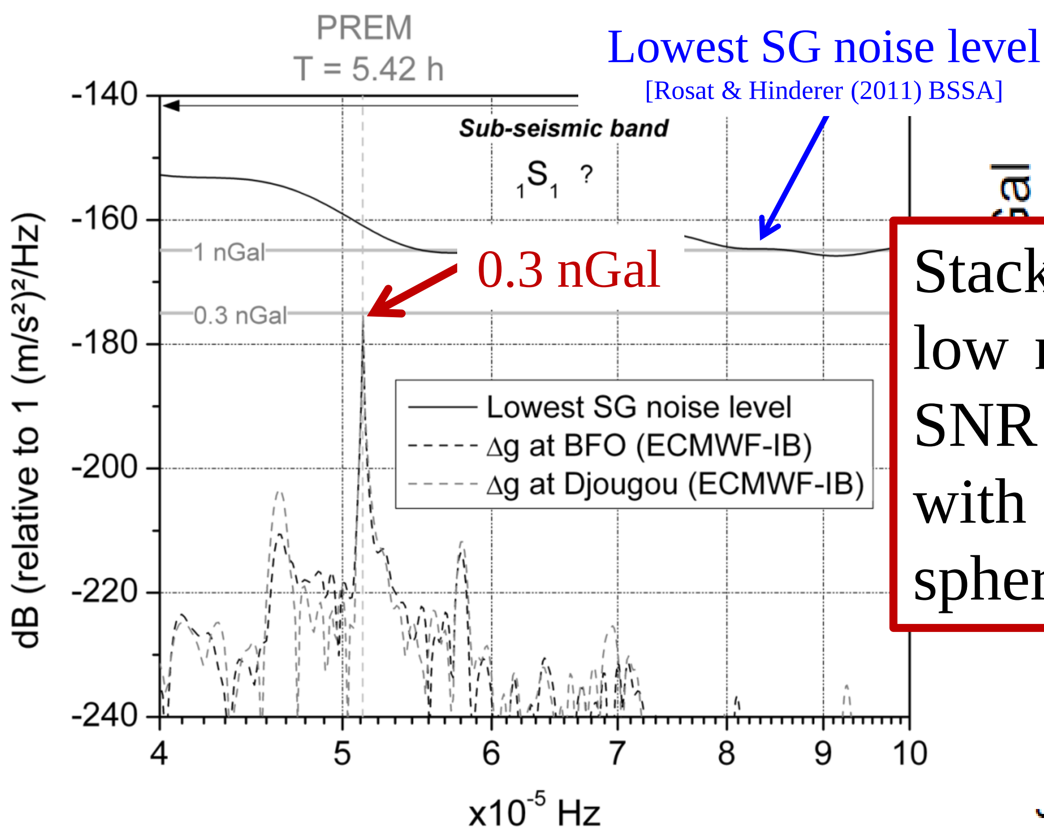
Forcing:

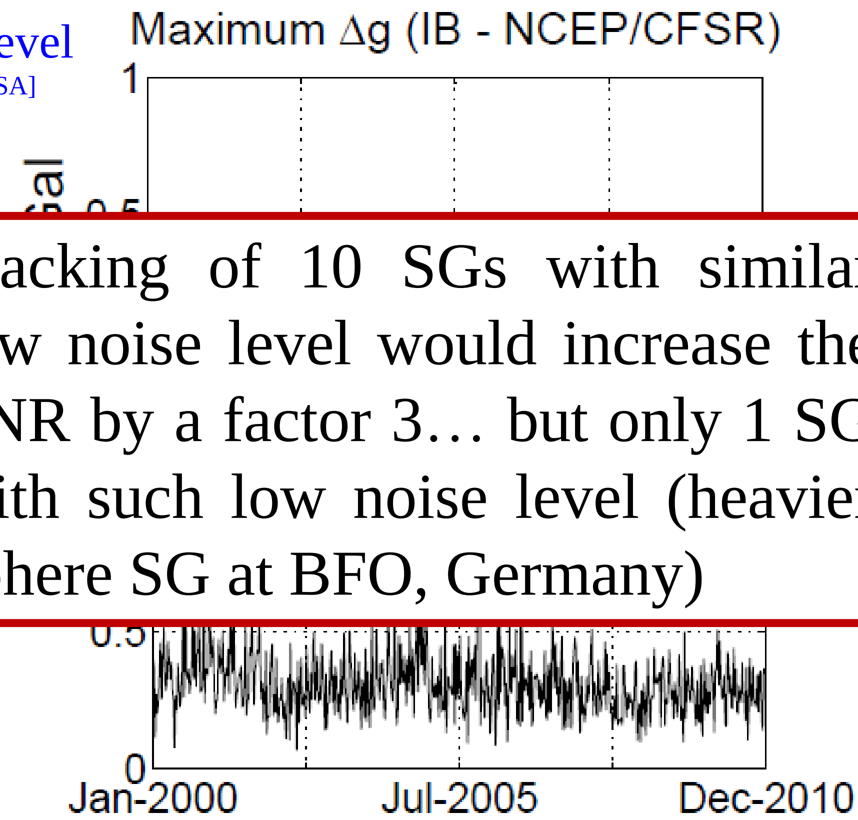
- Hourly degree-one ECMWF atmospheric pressure field during August 2008;
- Hourly degree-one NCEP/CFSR from 2000 until 2011.

Response of the oceans: inverted (IB) and a non-inverted barometer (NIB). [Rosat et al. (2014) PEPI]

Surface atmospheric load

ECMWF and NCEP/CFSR





Stacking of 10 SGs with similar low noise level would increase the SNR by a factor 3… but only 1 SG with such low noise level (heavier sphere SG at BFO, Germany)

Forcing:

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- Hourly degree-one NCEP/CFSR from 2000 until 2011.

[Rosat et al. (2014) PEPI]

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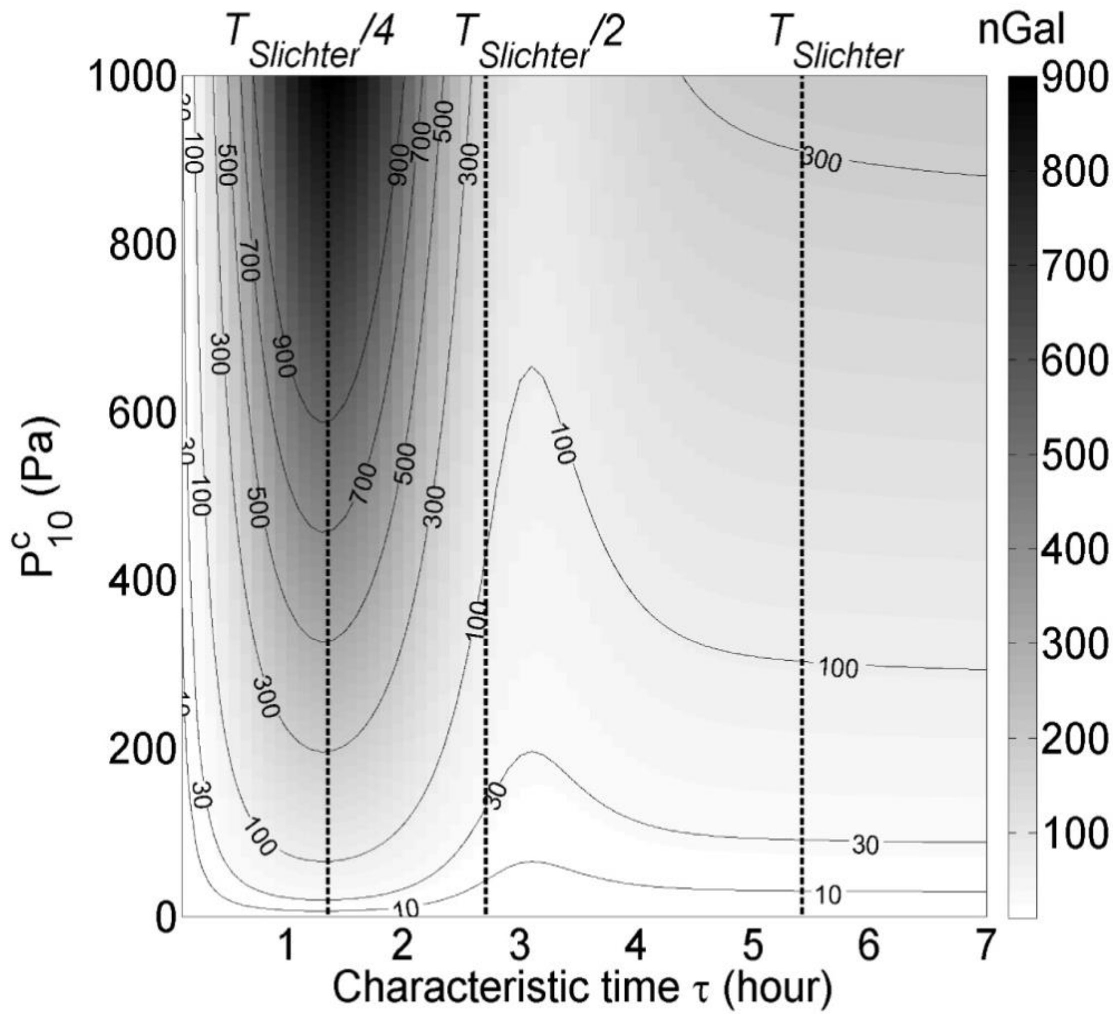
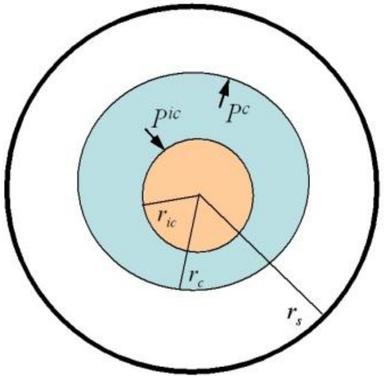
Pressure flow at the core boundaries: analytical model





Zonal degree-one pressure flow at CMB

$$P^{CMB} = P_{10}^{c} \cos\theta \;\; e^{-\left(\frac{t-T_0}{\tau}\right)^2}$$

[Rosat & Rogister 2012]
Results analog to Greff-Lefftz and Legros (2007)

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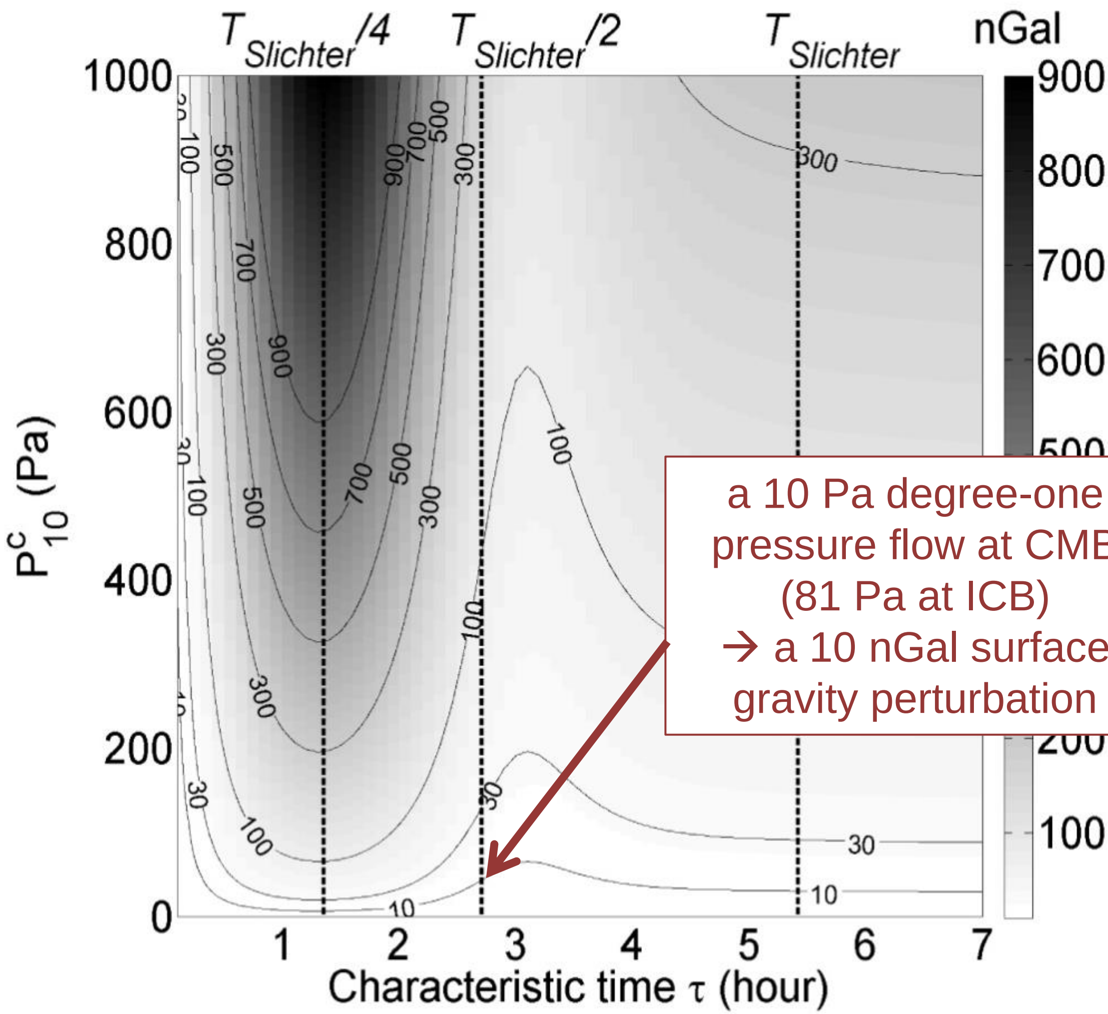
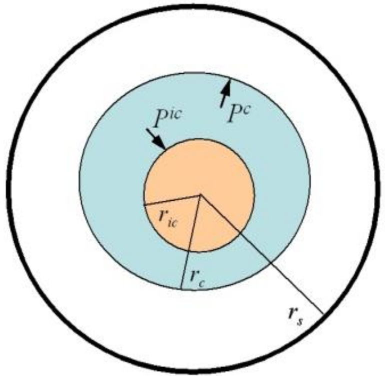


a 10 Pa degree-one pressure flow at CMB (81 Pa at ICB)
→ a 10 nGal surface gravity perturbation



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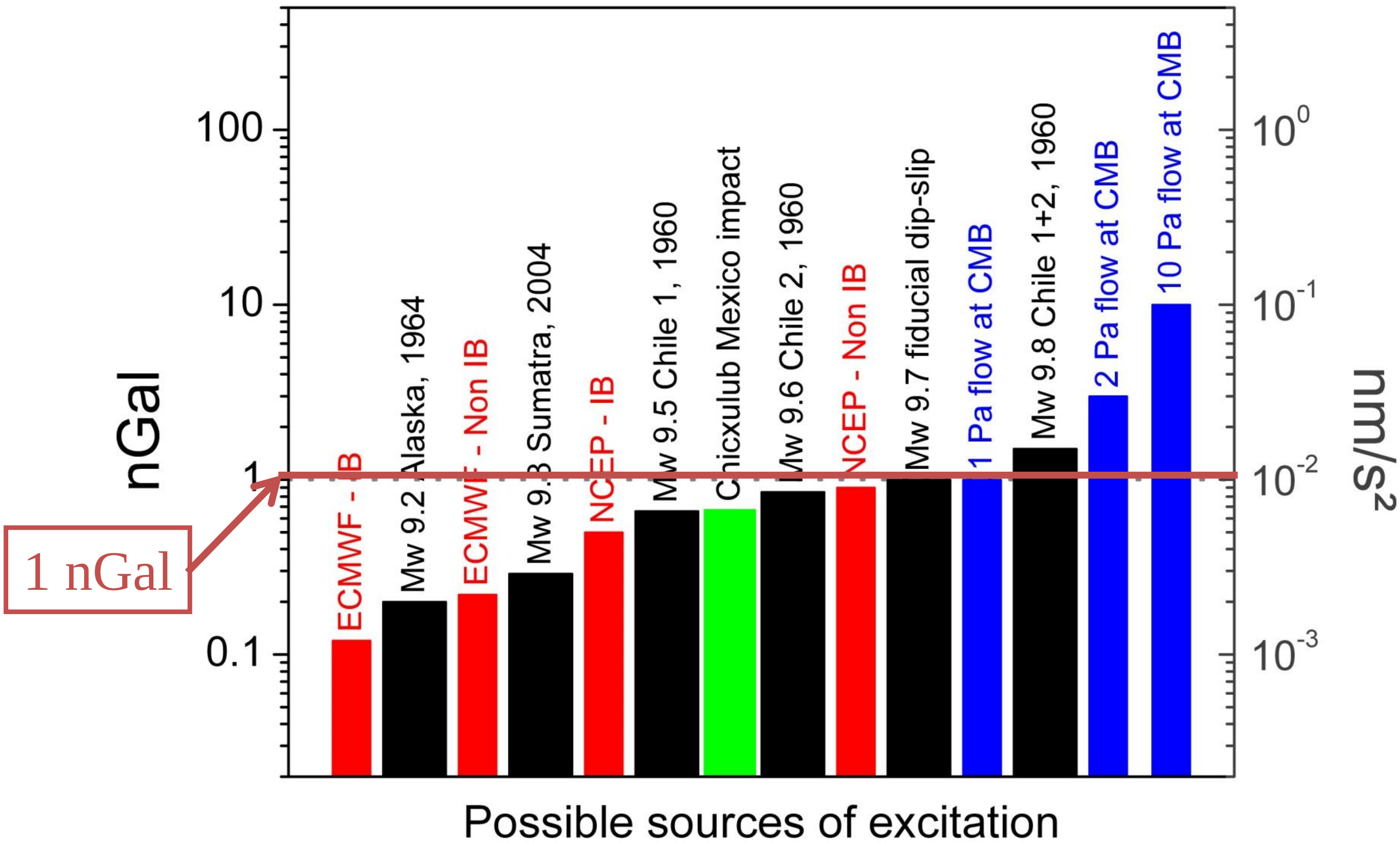
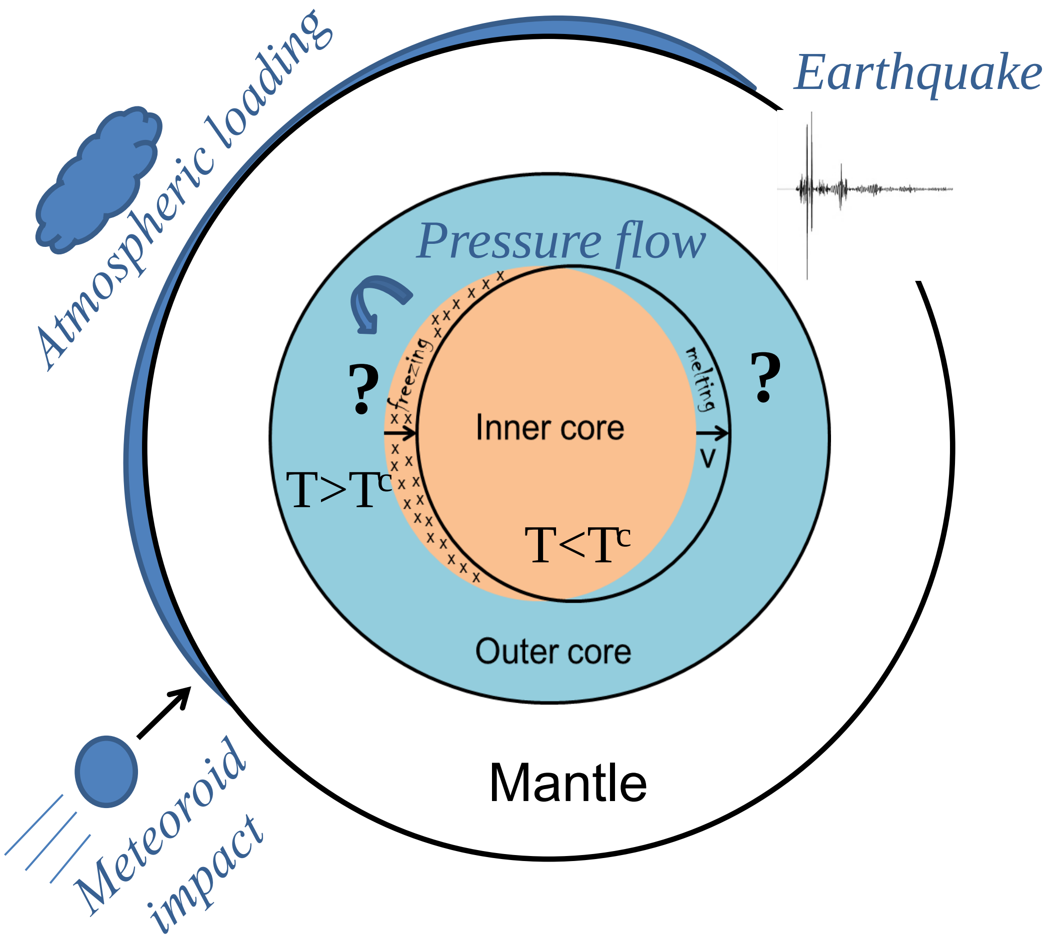
Maximum surface amplitudes for the Slichter mode



Thermal effects



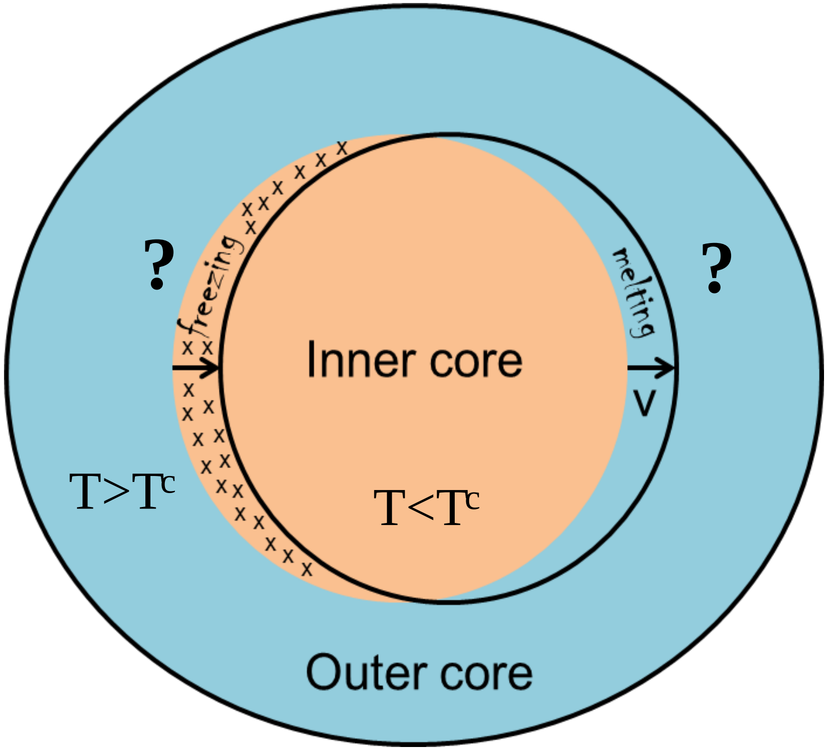
Thermal effects

Introduction of phase transformations at ICB:
Grinfeld & Wisdom 2010; Coyette et al. 2012

Instantaneous phase transformations

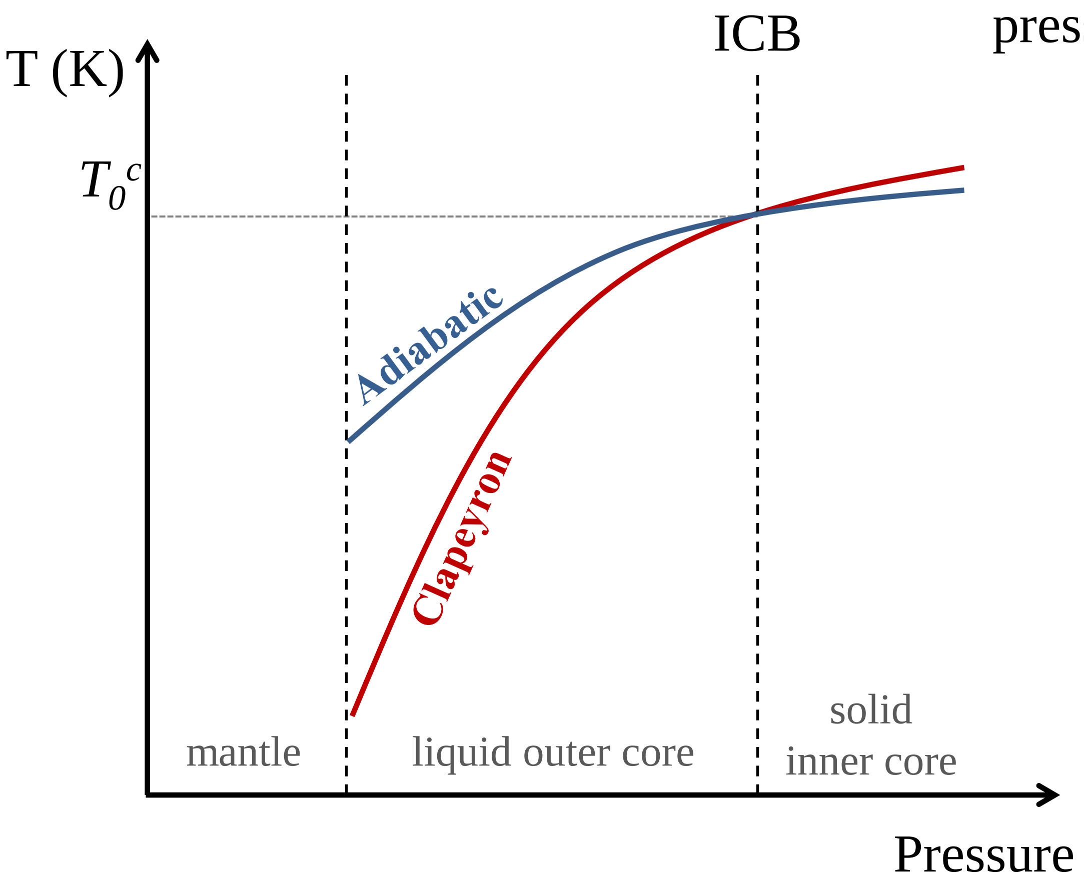
↓

Slichter mode periods of the **order of ten minutes** *(instead of 5.42 h for PREM)*



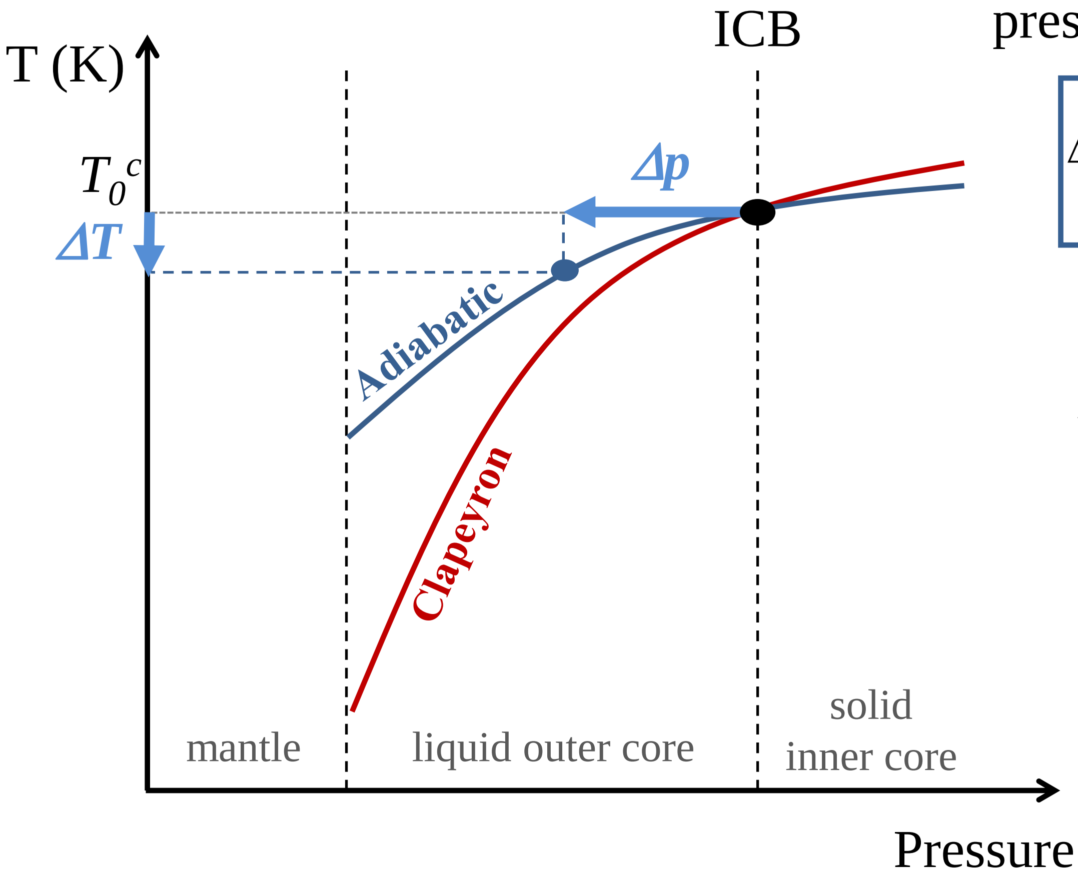
Thermal effects

During translation, Lagrangean pressure change Δp



- At the ICB, $T_0 = T_0^c$, critical temperature for phase change between liquid and solid.

Thermal effects



During translation, Lagrangean pressure change Δp

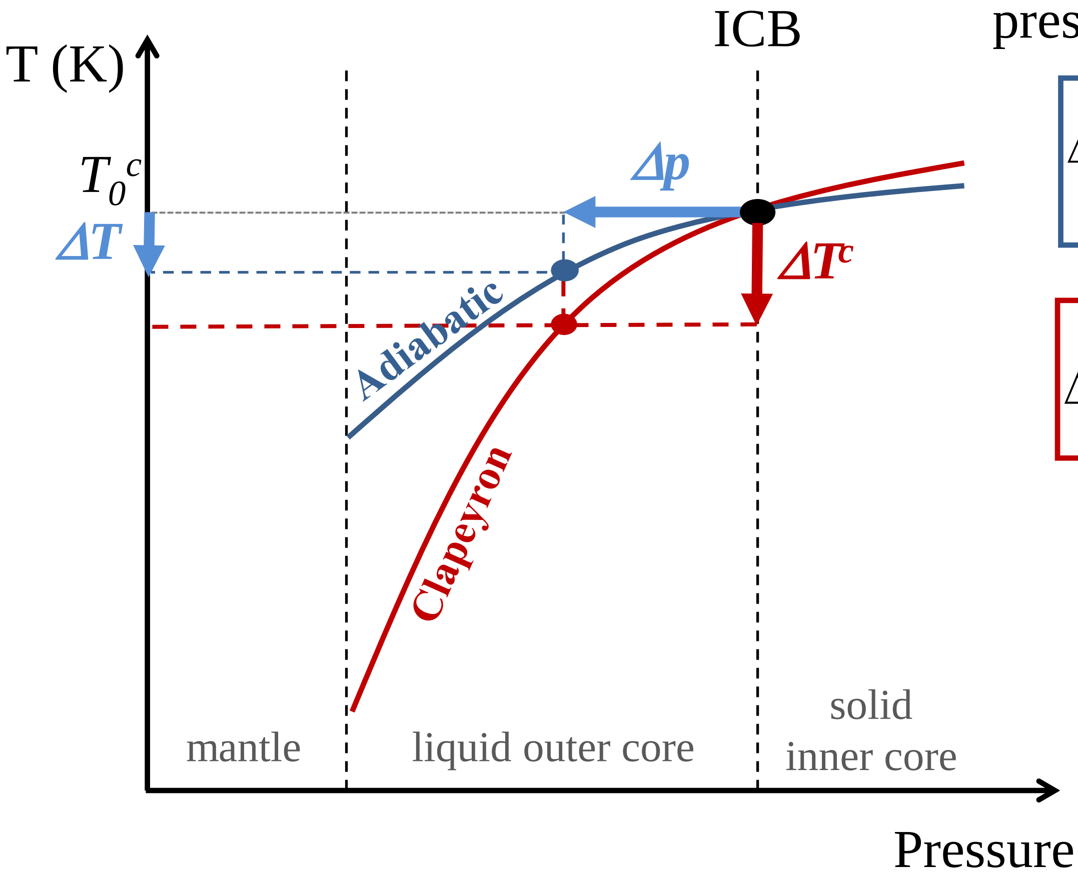
$$\Delta T = \frac{\alpha_p T_0}{\rho_c C_p} \Delta p$$

Adiabaticity

α_p : coefficient of thermal expansion
c_p : specific heat at constant pressure
ρ_c : fluid core density

- At the ICB, $T_0 = T_0^c$, critical temperature for phase change between liquid and solid.

Thermal effects



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$$\Delta T = \frac{\alpha_p T_0}{\rho_c C_p} \Delta p$$

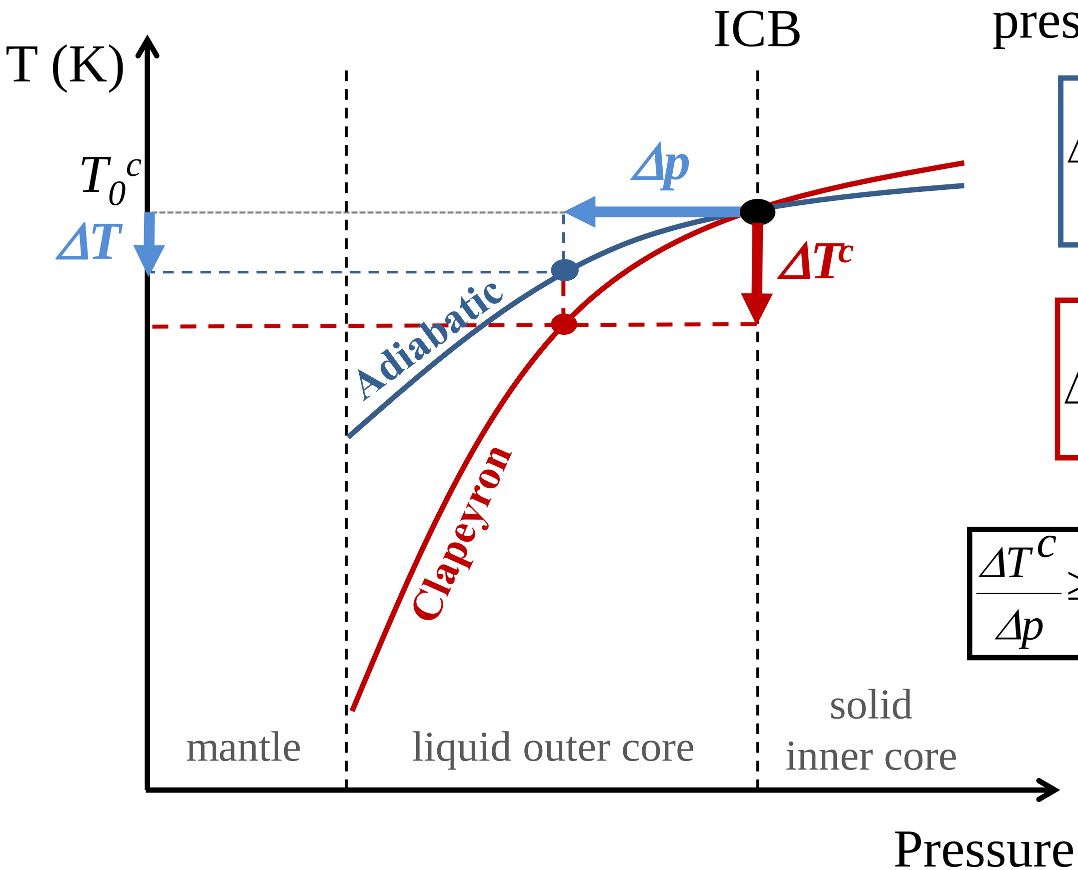
Adiabaticity

$$\Delta T^c = \frac{v_1 T_0^c}{L} \Delta p$$

Clausius-Clapeyron equation

- At the ICB, $T_0 = T_0^c$, critical temperature for phase change between liquid and solid.

Thermal effects



During translation, Lagrangean pressure change Δp

$$\Delta T = \frac{\alpha_p T_0}{\rho_c C_p} \Delta p$$ Adiabaticity

$$\Delta T^c = \frac{v_1 T_0^c}{L} \Delta p$$ Clausius-Clapeyron equation

$$\frac{\Delta T^c}{\Delta p} \geq \frac{\Delta T}{\Delta p}$$ → **supercooling** at ICB

- At the ICB, $T_0 = T_0^c$, critical temperature for phase change between liquid and solid.

Thermal effects

supercooling at ICB → development of dendrites (ramified crystalline structure) at ICB

Speed of solidification at the ICB = speed of growth of dendrites:

$$v_d = \xi\left(\Delta T^c - \Delta T\right)^{\eta}$$

(Wu and Rochester 1994)
(Flemings, 1974)

$\xi = 0.222,\ \eta = 1.84$

Speed of translation at the ICB:

$$V_t = f_0 u$$

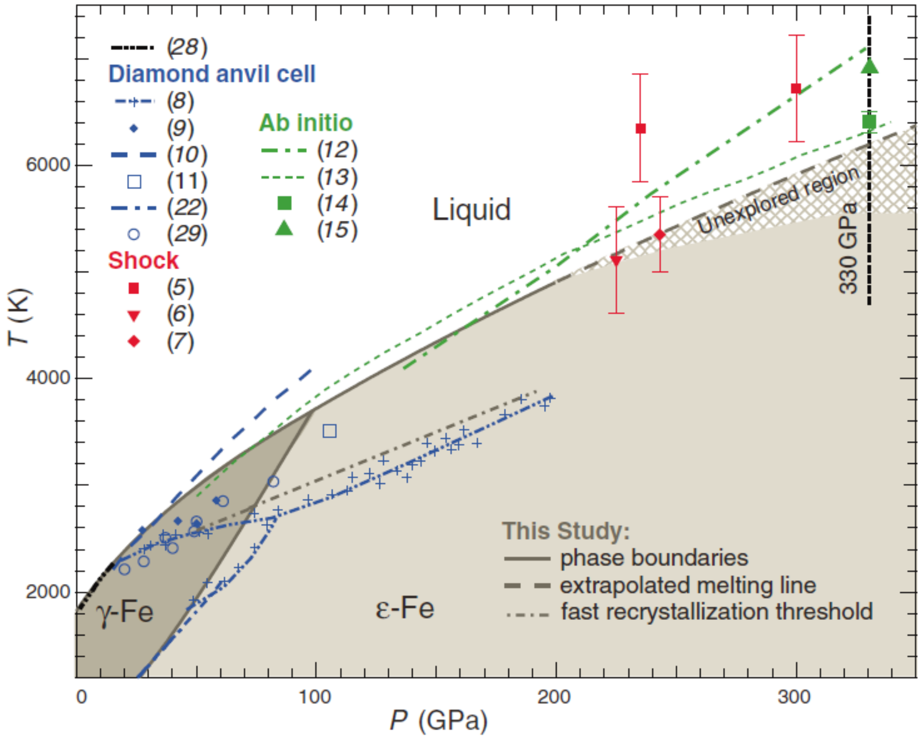
u: IC displacement (a few mm)
f_0: ${}_1S_1$ frequency ~ 5.12510^{-5} Hz

Thermal effects

Excitation source	Max. IC displacement (mm)	ΔT^c-ΔT (K)	Pressure change at ICB (hPa)	ICB Velocity V_t (m/s)	Growth Velocity v_d (m/s)
Pressure flows in the core (CMB: 150 Pa, ICB: 1217 Pa)	775	$5.4\ 10^{-5}$	415	$4\ 10^{-5}$	$3\ 10^{-11}$
Pressure flows in the core (CMB: 10 Pa, ICB: 81 Pa)	52	$3.6\ 10^{-6}$	28	$2.6\ 10^{-6}$	$2.2\ 10^{-13}$
ECMWF - IB (Aug. 2008)	0.5	$3.3\ 10^{-8}$	0.25	$2.4\ 10^{-8}$	$3.7\ 10^{-17}$
NCEP - non-IB (2000 - 2010)	3.2	$2.2\ 10^{-7}$	1.7	$1.6\ 10^{-7}$	$1.3\ 10^{-15}$

NO phase change during IC oscillation ← $v_d/v_t < 10^{-6}$

Thermal effects



Phase stability domains for Fe.

Anzellini et al. 2013, Melting of Iron at Earth's Inner Core Boundary Based on Fast X-ray Diffraction, *Science*

ICB = phase transition; · no mushy or slurry layer above the ICB; · adiabatic process; · no change of composition during the motion; use of Clapeyron equation (only valid for 1st order phase transformations), simple dendritic growth theory (transition interface, interfacial shape…) from an unstable crystal-melt interface (but **presence of impurities** S, Si, O in the melt), etc…

Summary on the Slichter mode

- Maximum surface gravity effect for known sources **< 1 nGal** and lowest **SG noise level** at Slichter frequency: **~2 nGal**;
- **Stacking 10 worldwide SGs of 2 nGal** low noise levels would improve the signal-to-noise ratio by a factor 3 (but today only SG at the Black Forest Observatory, Germany, has such a low noise level);
- Largest excitation amplitudes are reached for pressure flow acting at the core boundaries but actual flow amplitudes at such time-scales are unknown;
- Speed of translation of the IC >> growth velocity of dendrites, even for a 1-meter IC displacement ⇒ **no phase transformation during the oscillation.**

THANK YOU !

Density jump at ICB ?

<u>$\Delta\rho$(ICB) ?</u>

- Ratio of PKiKP/PcP wave amplitudes:
  - → < 450 kg m^{-3} [Koper & Pyle 2004]
  - → < 520 kg m^{-3} [Koper & Dombrovskaya, 2005]
- *PREM model → 600 kg m^{-3}*
- Normal modes → 820 kg m^{-3} [Masters & Gubbins 2003]

Gubbins et al. (2008) → model with large overall density jump between IC and OC of 800 kg/m^3 and a sharp density jump of 600 kg/m^3 at ICB

$\Delta\rho_{ICB}$ → **energy necessary to maintain the geodynamo process if driven by compositional convection linked to the IC growth → age of the IC**

$\Delta\rho_{ICB}$ larger → slower growth rate of the IC