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A REVIEW OF THE SLICHTER MODES: AN OBSERVATIONAL CHALLENGE

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Abstract

The free translational oscillations of the inner core, the so-called Slichter modes have been a subject of observational controversy. Its detection has never been undoubtedly validated. Also, it motivated additional theoretical studies. The search for the Slichter modes was invigorated by the development of worldwide data recorded by superconducting gravimeters (SGs) of the Global Geodynamics Project. Thanks to their long-time stability and low noise level, these relative gravimeters are the most suitable instruments to detect the small gravity signals that would be expected from the Slichter modes. The theory is now better understood and the most recent computations predict eigenperiods between 4 h and 6 h for the seismological reference PREM Earth model. A more recent study states that the period could be much shorter because of the kinetics of phase transformations at the inner-core boundary (ICB). The observation of the Slichter modes is fundamental because, the restoring force being Archimedean, their periods are directly related to the density jump at the ICB. This parameter is still poorly known. The analysis from seismic PKiKP/PcP phases or from normal modes observation leads to discrepancies in ICB density contrast estimates. This parameter should satisfy both the constraints set by powering the geodynamo with a reasonable heat flux from the core, and PKP travel-times and normal mode frequencies.

This paper gives a review of the theoretical backgrounds as well as of the attempts to detect such free oscillations. Some possible excitation sources are also investigated to evaluate the expected amplitude of the Slichter modes. The seismic source has been previously studied to demonstrate that an earthquake of magnitude $M_w = 9.68$ would be necessary to excite the Slichter mode to the nanogal level ($\approx 10^{-12} g$ where g is the mean surface gravity) at the Earth's surface. Earthquakes are therefore not the most suitable source to excite the Slichter mode to a level sufficient for the SGs to detect the induced surface gravity effect. Surficial pressure flows acting in the core have also been considered as a possible excitation source. The later turns out to be the best way to excite

the translational motion of the inner core. However we have little information about the fluid pressure amplitudes acting in the core at those frequencies. The observation of this Earth's normal mode is still an open challenge and the development of new generations of instruments with lower noise at such frequencies would be the only chance of detection.

Introduction

The observation in an earth-tide gravimeter record of the Earth's free oscillations after the large 1960 Chile earthquake revealed a spectral peak of period 86 min that Slichter (1961) interpreted (erroneously) as being the signature of the translational oscillation of the inner core. Since then, we call this free oscillation the Slichter modes. They have been a subject of observational controversy since the first detection by Smylie (1992) of a triplet of frequencies that he attributed to these free oscillations of the inner core. This detection has been supported by Courtier et al. (2000) and Pagiatakis et al. (2007) but has never been validated by other authors (e.g. Hinderer et al., 1995; Jensen et al., 1995; Rosat et al. 2006; Guo et al. 2007). Also, it motivated additional theoretical studies (e.g. Crossley, 1992; Crossley et al., 1992; Rochester and Peng, 1993; Crossley and Rochester, 1996; Smylie and McMillan, 2000; Rieutord, 2002; Rogister, 2003). The search for the Slichter modes was indeed invigorated by the development of worldwide data recorded by superconducting gravimeters (SGs) of the Global Geodynamics Project (GGP; Hinderer and Crossley, 2000). Thanks to their long-time stability and low noise level (a few nGals at Slichter frequencies; $1 \text{ nGal} = 10^{-2} \text{ nm/s}^2 \approx 10^{-12} g$ where g is the mean surface gravity), these relative gravimeters are the most suitable instruments to detect the associated surface gravity perturbation (Hinderer et al., 1995; Rosat et al., 2003, 2004).

The observation of the Slichter modes is fundamental because, the restoring force being Archimedean, their periods are directly related to the density jump at the inner core boundary (ICB). This density jump is a key parameter for evaluating the gravitational energy released from the cooling and solidification of the core (Loper 1978; Masters 1979; Morse 1986). The crystallization of the Earth's fluid core is probably the most important source of energy to power the geodynamo (Verhoogen 1961; Gubbins 1977; Anderson and Young 1988). However the density at ICB is still poorly known: by analyzing seismic PKiKP/PcP phases, Koper and Pyle (2004) found that it should be smaller than 450 kg/m^3 , later increased to 520 kg/m^3 (Koper and Dombrovskaya, 2005), whereas Masters and Gubbins (2003) obtained $820 \pm 180 \text{ kg/m}^3$ from normal modes observation. Tkalcic et al. (2009) have shown that the uncertainties associated with the seismic noise might partially explain such discrepancies in ICB density contrast estimates. Gubbins et al. (2008) have proposed a model with a large overall density jump between the inner and outer cores of 800 kg/m^3 and a sharp density jump of 600 kg/m^3 at the ICB itself. Such a model satisfies both the constraints set by powering the geodynamo with a reasonable heat flux from the core, and PKP travel-times and normal mode frequencies. The value of the density jump at ICB for the PREM model (Dziewonski and Anderson, 1981) is 600 kg/m^3 .

Moreover a convincing detection of this normal mode could also constrain the viscosity at the ICB (e.g. Smylie and McMillan, 1998 and 2000; Rieutord, 2002). The estimates of the

core viscosity are spanning several orders of magnitudes, ranging from 10^{-2} to 10^{11} Pa.s, according to the method used: laboratory experiments, theoretical developments or observations. More details are given on the estimated values of this parameter in the section related to the damping of the inner core motion.

Theoretical Eigenperiod for the Slichter Mode

The first evidence of the existence of the translational oscillation of the inner core was proposed by Slichter in 1961. Alsop (1963) computed the elasto-gravitational free oscillations of a spherically stratified non-rotating Earth and provided the first theoretical evidence of the existence of the Slichter mode. Then Smith (1976) computed the normal mode eigensolutions of the Slichter modes for a rotating, slightly elliptical Earth model.

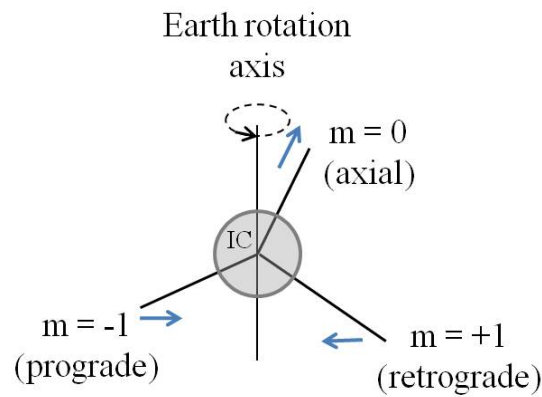


Figure 1. Schematic view of the three translational oscillations of the inner core.

In a spherical harmonic development, the Slichter mode corresponds to a ($l = 1$) degree-one spheroidal mode. When we consider an elliptically rotating Earth, the Slichter mode is split into three modes with harmonic orders $m = -1, 0$ and 1 , hence the so-called Slichter triplet. Smith (1976) also described the adjacent fluid particles motions associated with the motion of the solid inner core. In the equatorial plane, the fluid particles have an elliptical trajectory with a polarization opposite to the polarization of the inner core motion. The difference between the trajectories for $m = -1$ and $m = +1$ is principally due to the Coriolis forces. The center of mass of the inner core has a circular motion but the inner core does not rotate. A spear stuck into the inner core would remain parallel to its initial position (Smith, 1976). So the Slichter modes consist of three translational oscillations (Figure 1): two translations in the equatorial plane corresponding to prograde ($m = -1$) and retrograde ($m = +1$) modes and one axial mode ($m = 0$) along the axis of rotation. The terms retrograde and prograde refer to the sense of motion of the center of mass of the inner core with respect to the Earth's steady rotation. Smith (1976) obtained theoretical eigenperiods for the Slichter triplet between 4 h and 5 h (cf. Table 1).

Afterwards, many authors have proposed different values for the Slichter modes eigenperiods with periods ranging from 3 h to 7 h depending on the computation method and the Earth's model (cf. Table 1). An early calculation for an Earth model constrained by free oscillations observations by Dahlen and Sailor (1979), using second-order perturbation theory, but neglecting viscosity, gave periods in the 4 h to 5 h range. Crossley (1992) obtained values similar to those of Dahlen and Sailor (1979) for the CORE11 model (Widmer et al., 1988) while Smylie (1992), relying on his observational detection, obtained smaller eigenperiods for the 1066A Earth's model of Gilbert and Dziewonski (1975). Indeed Smylie (1992) and Smylie et al. (1993) proposed a theoretical computation of the Slichter modes, for the 1066A and CORE11 models, based on the sub-seismic approximation (Smylie and Rochester, 1981) that could explain their detected periods (cf. Table 1). However, Crossley et al. (1992) noted that Smylie's eigenperiods conflict significantly with all previously published periods, because of the inadequate use of static Love numbers instead of a dynamic theory. While Denis et al. (1997) argued that the main reason for the noted discrepancy may lie in the use of inadequate boundary conditions, combined with the fact that the computations rely on the sub-seismic approximation as well as on a variational approach.

Denis et al. (1997) have computed the eigenperiod for a non-rotating PREM model and obtained a value of 5.4202 h which confirms also the value obtained by Hinderer and Crossley (1993). Besides, they showed that because of the Earth's hydrostatic flattening, the density jump at the ICB should be less than PREM value and as a consequence, the Slichter period should be larger than 5.42 h.

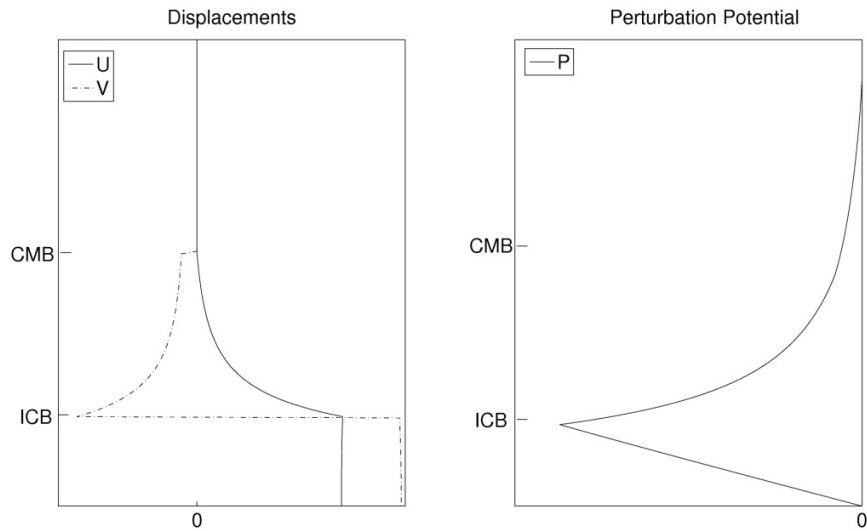


Figure 2. Displacement and potential eigenfunctions of the Slichter mode. U and V are respectively the radial and tangential displacements, and P is the perturbation of the gravitational potential. ICB refers to the inner core boundary and CMB to core-mantle boundary.

Table 1. Predicted and detected eigenperiods of the Slichter triplet. SSA stands for sub-seismic approximation

	Periods for the Slichter triplet (hour)			Method
	m = -1	m = 0	m = 1	
<i>Earth's models</i>				
<i>DG579</i>				
Smith (1976)	4.055	4.441	4.916	Normal Mode Theory
<i>Cal8</i>				
Smylie et al. (2009)	3.5168	3.7926	4.1118	Ekman boundary layer theory + inviscid
Smylie et al. (2009)	3.5840	3.7731	4.0168	Ekman boundary layer theory + viscous
<i>CORE11</i>				
Dahlen and Sailor (1979)	5.1663	5.8044	6.598	perturbation theory
Smylie (1992)	3.3432	3.5056	3.7195	perturbation theory + SSA + static Love numbers
Crossley (1992)	5.1603	5.7993	6.6029	Normal Mode Theory
Crossley et al. (1992)	3.950	4.438	4.896	perturbation theory + SSA + dynamic Love numbers
Smylie et al. (2009)	5.1280	5.7412	6.5114	Ekman boundary layer theory + inviscid
<i>I066A</i>				
Dahlen and Sailor (1979)	4.1284	4.5338	5.014	perturbation theory
Crossley (1992)	4.127	4.5329	5.0161	Normal Mode Theory
Smylie (1992)	2.6035	2.7023	2.8247	perturbation theory + SSA + static Love numbers
Rogister (2003)	4.129	4.529	5.024	Normal Mode Theory
Smylie et al. (1993; 2009)	4.0491	4.4199	4.8603	Ekman boundary layer theory + inviscid
<i>no viscosity</i>				
Crossley (1992)	3.95	4.438	4.896	Normal Mode Theory
Rieutord (2002)	3.894	4.255	4.687	Spectral method
<i>PREM</i>				
Dahlen and Sailor (1979)	4.7704	5.3129	5.975	perturbation theory
Crossley (1992)	4.7667	5.3104	5.9792	Normal Mode Theory
Rogister (2003)	4.77	5.309	5.991	Normal Mode Theory
Smylie et al. (2009)	4.6776	5.1814	5.7991	Ekman boundary layer theory + inviscid
<i>Busse's model</i>				
Rieutord (2002)	3.83361	4.18965	4.61423	Spectral method
<i>Detected peaks</i>				
Smylie (1992)	3.5820	3.7677	4.0150	Product spectrum of 4 SG records
Courtier et al. (2000)	3.5855	3.7680	4.0125	Multistation experiment
Pagiatakis et al. (2007)	4.269	4.516	4.889	Least-squares self-coherency of one SG record

Peng (1997) has studied the effect of a mushy zone at the ICB on the Slichter modes to show that the influence of the mushy boundary layer is substantial compared with some other effects, such as those from elasticity of the mantle, non-neutral stratification of the liquid

outer core and ellipticity of the Earth and centrifugal potential. He finally set a lower bound on the central eigenperiod of the Slichter mode of about 5.3 h for a PREM model.

Later on, Smylie et al. (2009) proposed periods in agreement with Crossley's values for the CORE11, 1066A and PREM Earth's models. Other estimates for the DG579 (Gilbert and Dziewonski, 1974, not published), Cal8 (Bolt and Urhammer, 1975) and Busse (1974) Earth models are also given in Table 1.

Finally, according to the most recent computations, the Slichter periods should be between 4 h and 6 h with a central period for the seismological reference PREM Earth's model around 5.3 h when computed by Rogister (2003) using the normal mode theory, or around 5.2 h when computed by Smylie et al. (2009) using the Ekman boundary layer theory of a dynamic viscometer oscillating in the contained, rotating fluid outer core.

However a more recent study by Grinfeld and Wisdom (2010) states that the period could be much shorter than 5 h because of the kinetics of phase transformations at the ICB. But their computation was based on simplistic assumptions and this effect still has to be studied more deeply.

Damping of the Inner Core Motion

Besides the large uncertainty on the period of the Slichter mode, we have poor constraints on its damping. The damping rate depends on the dissipation processes involved. Three sources of damping have been considered previously: the anelastic deformations of the inner core and mantle, the viscous and the magnetic dissipations in the core.

Crossley et al. (1991) have shown that the damping due to the seismic anelasticity of the inner core and mantle has a Q value of the order of 5000 with a corresponding damping time of 400 days.

The damping due to the outer core viscosity has been formulated by Smylie and McMillan (1998; 2000) and Rieutord (2002). The estimates of the dynamic viscosity of the fluid outer core range from $1.6 \cdot 10^{-2}$ Pa.s using laboratory experiments (Rutter et al. 2002), giving a Q value of the order of 10^7 , to $1.2 \cdot 10^{11}$ Pa.s (Smylie and McMillan, 2000) using the claimed Slichter modes by Courtier et al. (2000), giving a Q value less than 10 for a period of 5.5 hours. Smylie (1992) measured a quality factor of the resonance between 100 and 400, for a damping time of 6 days, and direct measurements on Figure 5 of Courtier et al. (2000) shows even higher values, while Ekman numbers found by Smylie and McMillan (2000) imply quality factors less than 10 (Rieutord, 2002). Mathews and Guo (2005) have proposed an upper limit of $1.7 \cdot 10^5$ Pa.s using nutation data corresponding to a Q value of 5000 (cf. also Guo et al. 2007).

The magnetic damping of the inner core oscillation has been studied by Buffett and Goertz (1995). They have shown that the Q value should be between $5.8 \cdot 10^5$ and 2200 for a magnetic field ranging from 0.0005 to 0.001 Tesla corresponding to an e-folding time of the oscillation as long as 108 years or as short as 150 days for a nominal period of 5.2 hours.

Such studies reveal that it should be difficult for the damping factor of the Slichter mode to be less than 2000, corresponding to a damping time of 144 days. In such a case, the induced surface gravity perturbation should be more easily detectable.

Excitation of the Slichter Mode

The mechanism of excitation for the Slichter mode is not well-known. It could be excited by some turbulent flows in the core or by a large earthquake. When looking at the displacement and potential eigenfunctions of the Slichter mode for a PREM Earth's model (Figure 2), we can see that the largest displacement of the Slichter mode occurs at the ICB. Then it is strongly attenuated as it goes through the liquid outer core. When the motion finally propagates to the surface of the Earth, it is very weak. So the induced surface signal is expected to be elusive.

The seismic excitation has been previously studied by Smith (1976), Crossley (1987; 1992) and Rosat (2007). The later authors have shown that the best natural focal mechanism to excite the Slichter mode is a vertical dip-slip source. Besides, the excitation amplitude is directly related to the seismic magnitude of the event. The largest event in the past was the 1960 Chile earthquake with a magnitude $M_w = 9.6$ for the main shock. A foreshock occurred with a magnitude $M_w = 9.5$ (Kanamori and Cipar, 1974). The combination of both events leads to a seismic source of magnitude $M_w = 9.8$ which would have excited the Slichter mode to the nanogal level ($1 \text{ nGal} = 10^{-2} \text{ nm/s}^2$), with a maximum amplitude of 1.5 nGal (cf. Table 2). Rosat (2007) has shown that the magnitude M_w necessary to excite the Slichter mode so that the induced surface gravity effect reaches 1 nGal should be at least $M_w = 9.68$ (Figure 3). Till now only the 1960 Chile earthquake would have been capable of exciting the Slichter mode to such a level.

Earthquakes are therefore not the most efficient way to excite the Slichter mode to a level sufficient for the SGs to detect the induced surface gravity effect.

Greff-Lefftz and Legros (2007) have considered a degree-one pressure flow acting at the outer core boundaries as a possible excitation mechanism. They computed the degree-one elasto-gravitational deformations for a simple Earth model (constituted of three homogeneous layers: a solid inner core, an incompressible fluid outer core and a rigid mantle) and estimated an excitation amplitude of 50 nGal at the Earth's surface for a pressure flow of about 150 Pa acting during a time close to the Slichter period (3 h for their Earth's model). More recently, Rosat and Rogister (2011) used the theory of the normal modes with the Green function formalism to compute also the excitation of the Slichter mode by a degree-one pressure acting at the outer core boundaries but for a more realistic PREM Earth's model. The computation leads to the surface gravity variations plotted in Figure 4 as a function of the time-duration and the amplitude of the acting pressure. Their results show larger excitation amplitudes than the one obtained by Greff-Lefftz and Legros (2007). The differences must certainly come from the use of different Earth's model, as the compressibility and the stratification of the liquid outer core have a large influence on the Slichter mode (Rogister 2003). Besides they showed that the largest perturbation of the surface gravity field occurs when the time duration τ of the acting pressure is smaller than half the Slichter period. In such a case, an 81 Pa pressure flow acting at the ICB (a corresponding 10 Pa flow at the CMB) is enough to induce a translation of the inner core of 50 mm corresponding to a 10 nGal surface gravity perturbation, which should be detectable by SGs (Rosat and Hinderer, 2011).

Table 2. Maximum excitation amplitude of the Slichter mode after major past earthquakes

Event	Chile 1	Chile 2	Chile 1+2	Alaska	Bolivia	Peru	Andaman-Sumatra
Date	1960	1960	1960	1964	1994	2001	2004
Moment (N.m)	2.7 10 ²³	3.5 10 ²³	6.2 10 ²³	7.5 10 ²²	2.6 10 ²¹	4.7 10 ²¹	1.1 10 ²³
Magnitude M _w	9.5	9.6	9.8	9.2	8.2	8.4	9.3 ¹
Depth (km)	25	50	38	50	640	30	28
Reference	Kanamori and Cipar (1974)			Kanamori (1970)	Harvard 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	1.520	0.336	0.02 ²	-	-
Rosat (2007)	0.656	0.853	1.509	0.193	0.007	0.010	0.286

¹ Stein and Okal (2005)

² personal communication

* The Harvard Centroid Moment Tensor is available at: <http://www.globalcmt.org>

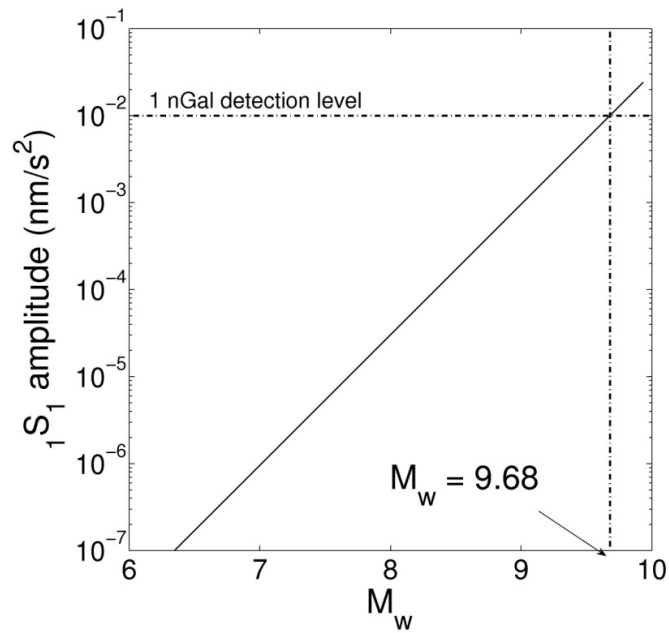


Figure 3. Surface gravity effect associated to the excitation of the Slichter mode by a vertical dip-slip source earthquake (same focal mechanism as for the 1960 Chilean earthquake) as a function of the seismic magnitude.

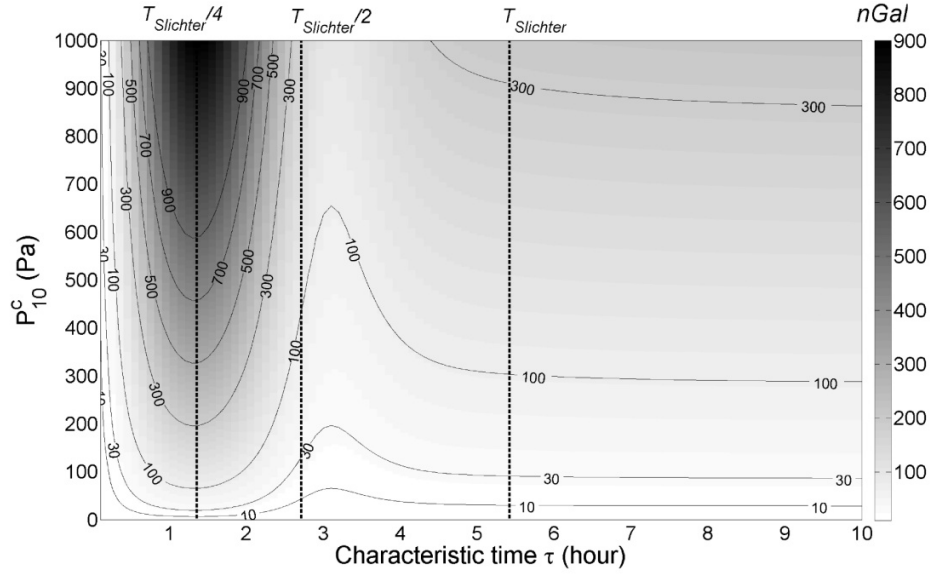


Figure 4. Surface gravity perturbation in nGal induced by the Slichter mode excited by a zonal degree-one pressure flow acting at the CMB for different excitation time-scales and various pressure amplitudes. The vertical dotted lines respectively correspond to one quarter of the Slichter period, one half of the Slichter period and the Slichter period (after Rosat and Rogister, 2011).

Rosat and Rogister (2011) have also computed the excitation amplitude of the Slichter mode induced by a degree-one pressure load applied on the Earth's surface. When applying a surface pressure variation of 1000 Pa during $2\tau = 3\text{h}$, the induced surface gravity perturbation can reach an amplitude of 5 nGal corresponding to an inner-core translation of 15 mm. When the excitation time-scale is larger than the Slichter period, the excitation amplitude is smaller.

Note that previous computations were made with analytical expressions for the pressure flow as we have no information about the pressure flow in the core at such time-scales and surface atmospheric or oceanic data have a time resolution larger than the Slichter period.

Another efficient way to trigger a degree-one motion could be a sudden shock at the Earth's surface. Rosat and Rogister (2011) have also computed the amplitude of the Slichter mode excited by the impact of a meteoroid. The drag by the atmosphere was taken into account in their computation as well as the possible breakup of the extra-terrestrial object. They used a seismic efficiency parameter to convert the shock wave generated by the impact into an equivalent seismic energy. Then the problem turns out to be equivalent to the excitation by a seismic explosion at the Earth's surface. Their results have shown that even for the biggest meteoroid, the surface excitation amplitude of the Slichter mode is less than 1 nGal (cf. Table 3). However, they used a seismic efficiency of $k_s = 10^{-4}$ and there is a large uncertainty on this parameter as its value can range from 10^{-5} to 10^{-3} (Schultz and Gault, 1975). With a seismic efficiency ten times larger, i.e. $k_s = 10^{-3}$, the meteoroid impact which created the Chicxulub crater in Mexico 64.98 million years ago, would have released a seismic energy equivalent to an $M_w = 10.2$ explosive source. Such a mechanism would have excited the inner-core translational mode so that the associated surface gravity perturbation

would have reached 4 nGal. This large gravity signature would have been detectable by SGs but of course the consequences would have been devastating.

Table 3. Some known meteoroid impacts on the Earth. The impact angle is supposed to be 45 degrees and the velocity of the extraterrestrial object when it enters the Earth's atmosphere is 20 km/s. The seismic efficiency has been fixed to $k_s = 10^{-4}$.

Location	Date (AD or My BP)	Diameter (m)	Density (kg/m ³)	M _w	Δg (nm/s ²)
Tunguska Fireball, Siberia	1908 AD	60	2700 (rock)	No impact	
Ries Crater, Germany	15.1 ± 0.1	1500	2700 (rock)	7.4	3 10 ⁻⁶
Rochechouart, France	214 ± 8	1500	3350 (stony-iron)	7.5	3 10 ⁻⁶
Chesapeake Bay, USA	35.5 ± 0.3	2300	2700 (rock)	7.8	10 ⁻⁵
Chicxulub, Mexico	64.98 ± 0.05	17500	2700 (rock)	9.6	4 10 ⁻³

As a conclusion, seismic events, extra-terrestrial object impacts and surface pressure loads are not much efficient to excite the Slichter mode with an amplitude large enough to be detected at the surface by SGs. On the other hand, a degree-one pressure flow acting at the outer core boundaries is the best mechanism to excite the translational modes of the inner core. However no computation has been done using actual values for the surface pressure variations.

Search for the Slichter Triplet

Although the Slichter mode is crucial in determining the density contrast across the ICB, its detection remains very challenging. As seen in the previous section, the difficulty mainly comes from its small predicted surface amplitude. The search for its surface signature began with the venue of relative superconducting gravimeters. SGs are currently the most suitable instruments, in terms of stability, accuracy and precision, to detect the surface gravity effect induced by the translational oscillation of the inner core. However, as shown by Rosat et al. (2004) and Rosat and Hinderer (2011), their noise levels at Slichter frequencies are at the limit of the nanogal amplitude. As a consequence, only a combination of the best SG records could help detecting nanogal signals induced by the core.

The observational controversy started with the claim of an identification of the Slichter triplet in the product spectrum of four SG records by Smylie (1992). Then various authors combined SG records to try to confirm Smylie's first claim: for instance Jensen et al. (1995), using a product spectrum, and Hinderer et al. (1995), using a cross spectrum of SG data, could not validate Smylie's first detection. Later, Courtier et al. (2000) proposed a stacking

method, called the multi-station experiment, which enhances the harmonic degree-one modes and suggested a candidate for the Slichter triplet very similar to the one detected by Smylie (1992).

Then, some more recent attempts by Rosat et al. (2003; 2006) and Guo et al. (2006, 2007) using sophisticated stacking and detection methods on less noisy SG data have not led to the confirmation of this potential candidate. Later, Rosat et al. (2007) have tried a wavelet-analysis method and Rosat et al. (2008) have used a non-linear harmonic analysis tool on various stacked SG datasets, in vain. On the other hand, Pagiatakis et al. (2007) have applied a least-squares self-coherency analysis on one SG record from Cantley (Canada) and detected a triplet of frequencies close to Smylie's triplet. However they performed the analysis on only one site while the Slichter mode signature would be global. Moreover, theoretical developments by Rieutord (2002) and Rogister (2003) concluded that Smylie's observed frequency was inconsistent with the predictions.

No unambiguously new detection of the Slichter modes has been proposed yet.

Conclusion

We have reviewed the major past theoretical developments concerning the Slichter triplet as well as the main efforts performed for its detection in superconducting gravimetry data. Some possible mechanisms of excitation have also been investigated. From this review, we can conclude that the Slichter mode eigenperiod should be around 5 h with a lower bound for the quality factor of 2000. Besides, it would be best excited by a degree-one pressure flow acting at the outer core boundaries at time-scales shorter than its period. As we do not know the pressure flow in the core at such short time-scales, there is still some uncertainty on the expected surface excitation amplitude of the Slichter mode.

The detectability of the Slichter modes depends on the magnitude of the response of the inner core to the geodynamic excitation process and on its decay rate. As the Slichter modes have not yet been undoubtedly detected, we can suppose that their amplitudes are too small so that they are hidden by the noise. Consequently, only instruments with lower noise at sub-seismic frequencies would be able to detect its signature at the Earth's surface.

Bibliography

- Alsop, L. E. (1963). Free spheroidal vibrations of the earth at very long periods, 2, Effect of rigidity of the inner core. *Bull. Seism. Soc. Am.*, 53, 503.
- Anderson, O. L. and Young, D. A. (1988). Crystallization of the Earth's inner core. In *Structure and Dynamics of Earth's Deep Interior*, pp. 83-90, eds Smylie, D. E. and Hide, R., AGU.
- Bolt, B. A., Urhammer R. (1975), Resolution techniques for density and heterogeneity in the Earth. *Geophys. J. R. Astron. Soc.*, 42, 419-435.

- Buffett, B. and Goertz, D. E. (1995). Magnetic damping of the translational oscillations of the inner core. *Geophys. J. Int.*, 120, 103-110.
- Busse, F. H. (1974). On the free oscillation of the Earth's inner core. *J. Geophys. Res.*, 79, 753-757.
- Courtier, N., Ducarme, B., Goodkind, J., Hinderer, J., Imanishi, Y., Seama, N., Sun, H., Merriam, J., Bengert, B., Smylie, D.E. (2000). Global superconducting gravimeter observations and the search for the translational modes of the inner core. *Phys. Earth Planet. Int.*, 117, 320.
- Crossley, D. (1987). The excitation of core modes by Earthquakes. In *Structure and Dynamics of Earth's Deep Interior, Geophys. Monogr.*, 46/IUGG Ser., Vol. 1, pp. 41-50, eds D.E. Smylie and R. Hide, AGU, Washington, DC.
- Crossley, D. J. (1992). Eigensolutions and seismic excitation of the Slichter mode triplet for a fully rotating Earth model. *EOS*, 73, 60.
- Crossley, D. J., Hinderer, J. and Legros, H. (1991). On the excitation, detection and damping of core modes. *Phys. Earth Planet. Int.*, 68, 97-116.
- Crossley, D. J., Rochester, M. G., Peng, Z. R. (1992). Slichter modes and love numbers. *Geophys. Res. Lett.*, 19, 1679-1682.
- Crossley, D. J., Rochester, M. G. (1996). The subseismic approximation in core dynamics. II. Love numbers and surface gravity. *Geophys. J. Int.*, 125, 839-840.
- Dahlen, F. A. and Sailor, R. V. (1979). Rotational and elliptical splitting of the free oscillations of the Earth. *Geophys. J. R. Astron. Soc.*, 58, 609-623.
- Denis, C., Rogister, Y., Amalvict, M., Delire, C., Ibrahim Denis A., Munhoven, G. (1997). Hydrostatic flattening, core structure, and translational mode of the inner core, *Phys. Earth Planet. Int.*, 99, 195-206.
- Dziewonski, A. M., Anderson, D. L. (1981). Preliminary reference Earth model (PREM). *Phys. Earth Planet. Int.*, 25, 297-356.
- Gilbert, F. and Dziewonski, A. (1975). An application of normal mode theory to the retrieval of structural parameters and source mechanisms from seismic spectra. *Phil. Trans. R. Soc. Lond.*, A278, 187-269.
- Greff-Lefftz, M. and Legros, H. (2007). Fluid core dynamics and degree-one deformations: Slichter mode and geocenter motions. *Phys. Earth Planet. Int.*, 161, 150-160.
- Grinfeld, P. and Wisdom, J. (2010). The effect of phase transformations at the inner core boundary on the Slichter modes. *Phys. Earth Planet. Int.*, 178, 3-4, 183-188.
- Gubbins, D. (1977). Energetics of the earth's core. *J. Geophys.*, 43, 453-464.
- Gubbins, D., Masters, G. and Nimmo, F. (2008). A thermochemical boundary layer at the base of Earth's outer core and independent estimate of core heat flux. *Geophys. J. Int.*, 174, 1007-1018.

- Guo, J. Y., Dierks, O., Neumeyer, J. and Shum, C. K. (2006). Weighting algorithms to stack superconducting gravimeter data for the potential detection of the Slichter modes. *J. Geodyn.*, 41, 326-333.
- Guo, J. Y., Dierks, O., Neumeyer, J. and Shum, C. K. (2007). A search for the Slichter modes in superconducting gravimeter records using a new method. *Geophys. J. Int.*, 168, 507-517.
- Hinderer, J. and Crossley, D. (1993). Core dynamics and surface gravity change. In: J.-L. LeMouél, D.E. Smylie and T. Herring (Editors), *Dynamics of the Earth's Deep Interior and Earth Rotation. AGU Geophysical Monograph*, 72, IUGG, vol. 12, 1-16.
- Hinderer, J., Crossley, D. and Jensen, O. (1995). A search for the Slichter triplet in superconducting gravimeter data. *Phys. Earth Planet. Int.*, 90, 183-195.
- Hinderer, J. and Crossley, D. (2000). Time variations in gravity and inferences on the Earth's structure and dynamics. *Surv. Geophys.*, 21, 1-45.
- Jensen, O. G., Hinderer, J. and Crossley, D.J. (1995). Noise limitations in the core-mode band of superconducting gravimeter data. *Phys. Earth Planet. Int.*, 90, 169-181.
- Kanamori, H. (1970). The Alaska earthquake of 1964: Radiation of long-period surface waves and source mechanism. *J. Geophys. Res.*, 75, pp. 5029-5040.
- Kanamori, H. and Cipar, J. J. (1974). Focal process of the great Chilean earthquake May 22, 1960. *Phys. Earth Planet. Int.*, 9, 128-136.
- Koper, K. D. and Dombrovskaya, M. (2005). Seismic properties of the inner core boundary from PKiKP/PcP amplitude ratios. *Earth Planet. Sci. Lett.*, 237, 680-694.
- Koper, K. D. and Pyle, M. L. (2004). Observations of PKiKP/PcP amplitude ratios and implications for Earth structure at the boundaries of the liquid core. *J. Geophys. Res.*, 109, B03301.
- Loper, D. E. (1978). The gravitationally powered dynamo. *Geophys. J. R. astr. Soc.*, 54, 389-404.
- Masters, G. (1979). Observational constraints on the chemical and thermal structure of the Earth's deep interior. *Geophys. J. R. astr. Soc.*, 57, 507-534.
- Masters, G. and Gubbins, D. (2003). On the resolution of the density within the Earth. *Phys. Earth Planet. Int.*, 140, 159-167.
- Mathews, P. M. and Guo, J. Y. (2005). Visco-electromagnetic coupling in precession-nutation theory. *J. Geophys. Res.*, 110(B2), B02402. doi:10.1029/2003JB002915.
- Morse, S. A. (1986). Adcumulus growth of the inner core. *Geophys. Res. Lett.*, 13, 1557-1560.
- Pagiatakis, S. D., Yin, H. and Abd El-Gelil, M. (2007). Least-squares self-coherency analysis of superconducting gravimeter records in search for the Slichter triplet. *Phys. Earth Planet. Int.*, 160, 108-123.

- Peng, Z. R. (1997). Effects of a mushy transition zone at the inner core boundary on the Slichter modes. *Geophys. J. Int.*, 131, 607-617.
- Rieutord, M. (2002). Slichter modes of the Earth revisited. *Phys. Earth Planet. Int.*, 131, 269-278.
- Rochester, M. G. and Peng Z. R. (1993): The Slichter modes of the rotating Earth: a test of the subseismic approximation. *Geophys. J. Int.*, 111, 575-585.
- Rogister, Y. (2003). Splitting of seismic free oscillations and of the Slichter triplet using the normal mode theory of a rotating, ellipsoidal earth. *Phys. Earth Planet. Int.*, 140, 169-182.
- Rosat, S. (2007). Optimal Seismic Source Mechanisms to Excite the Slichter Mode. *Int. Assoc. of Geod. Symposia, Dynamic Planet, Cairns (Australia)*, vol. 130, 571-577, Springer Berlin Heidelberg New York.
- Rosat, S. and J. Hinderer (2011). Noise levels of superconducting gravimeters: updated comparison and time-stability. *Bull. Seism. Soc. Am.*, vol. 101, no. 3, June 2011, doi: 10.1785/0120100217.
- Rosat, S. and Rogister, Y. (2011). Excitation of the Slichter mode by collision with a meteoroid or pressure variations at the surface and core boundaries. *Phys. Earth Planet. Int.* (submitted).
- Rosat, S., Hinderer, J., Crossley, D. J., Rivera, L. (2003). The search for the Slichter mode: comparison of noise levels of superconducting gravimeters and investigation of a stacking method. *Phys. Earth Planet. Int.*, 140 (13), 183-202.
- Rosat, S., Hinderer, J., Crossley, D. J., Boy, J. P. (2004). Performance of superconducting gravimeters from long-period seismology to tides. *J. of Geodyn.*, 38, 461-476.
- Rosat, S., Rogister, Y., Crossley, D. and Hinderer, J. (2006). A search for the Slichter Triplet with Superconducting Gravimeters: Impact of the Density Jump at the Inner Core Boundary. *J. of Geodyn.*, 41, 296-306.
- Rosat, S., Sailhac, P. and Gegout, P. (2007). A wavelet-based detection and characterization of damped transient waves occurring in geophysical time-series: theory and application to the search for the translational oscillations of the inner core. *Geophys. J. Int.*, 171, 55-70.
- Rosat, S., Fukushima, T., Sato, T. and Tamura, Y. (2008). Application of a Non-Linear Damped Harmonic Analysis method to the normal modes of the Earth. *J. of Geodyn.*, 45 (1), 63-71.
- Rutter, M. D., Secco, R. A., Uchida, T., Liu, H., Wang, Y., Rivers, M. L. and Sutton, S. R. (2002). Towards evaluating the viscosity of the Earth's outer core: an experimental high pressure study of liquid Fe-S (8.5 wt.% S). *Geophys. Res. Lett.*, 29(8), 1217. doi: 10.1029/2001GL014392.
- Schultz, P. H. and Gault, D. E. (1975). Seismic effects from major basin formation on the moon and Mercury. *The Moon*, 12, 159-177.

- Slichter, L. B. (1961). The fundamental free mode of the Earth's inner core. *Proc. Natl. Acad. Sci., USA*, 47, 186-190.
- Smith, M. L. (1976). Translational inner core oscillations of a rotating, slightly elliptical Earth. *J. Geophys. Res.*, 81 (17), 3055-3065.
- Smylie, D. E. (1992). The inner core translational triplet and the density near Earth's center. *Science*, 255, 1678-1682.
- Smylie, D. E. and Rochester, M. G. (1981). Compressibility, core dynamics and the subseismic wave equation. *Phys. Earth Planet. Int.*, 24, 308-319.
- Smylie, D. E., Hinderer, J., Richter, B. and Ducarme, B. (1993). The product spectra of gravity and barometric pressure in Europe. *Phys. Earth Planet. Int.*, 80, 135-157.
- Smylie, D. E., McMillan, D. G. (1998). Viscous and rotational splitting of the translational oscillations of Earth's solid inner core. *Phys. Earth Planet. Int.*, 106, 1-18.
- Smylie, D. E., McMillan, D. G. (2000). The inner core as a dynamic viscometer. *Phys. Earth Planet. Int.*, 117, 71-79.
- Smylie, D. E., Brazhkin, V. V. and Palmer, A. (2009). Direct observations of the viscosity of Earth's outer core and extrapolation of measurements of the viscosity of liquid iron. *Phys.-Usp.*, 52 (1), 79-92.
- Stein S. and E. Okal (2005). Speed and size of the Sumatra earthquake. *Nature*, 434, p. 581.
- Tkalcic, H., Kennett, B. L. N. and Cormier, V. F. (2009). On the inner-outer core density contrast from PKiKP/PcP amplitude ratios and uncertainties caused by seismic noise. *Geophys. J. Int.*, 179, 425-443.
- Verhoogen, J. (1961). Heat balance of the Earth's core. *Geophys. J.*, 4, 276-281.
- Widmer, R., G. Masters, F. Gilbert (1988), paper presented at the 17th International Conference on Mathematical Geophysics, Blanes, Spain, June 1988.