Condensed matter physics and experiments at very high pressures constrain possible explanations of apparently remote astronomical problems such as perturbations in the Earth's rotation.

Frontiers in Deep-Earth Physics

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There is abundant evidence that the Earth is an active planet: continents drift, mountains build up, earthquakes crack the crust, and volcanoes spew molten rock. Other less obvious signs of activity consist in the existence of a magnetic field, shown by Gauss to be of internal origin, and of irregularities in the Earth's rotation. All these phenomena have a deep-seated origin: convection of the hot, very viscous, almost 3000 km-thick rocky mantle (cover illustration) evacuates internal heat and drives plate tectonics and its various manifestations. Deeper down, in the electrically conducting fluid core, convection currents generate the Earth's magnetic field; coupling between the core and the mantle is responsible for fluctuations of long period in the length of day.

The heat in the Earth's core is essentially due to secular cooling of the core and to the release of light elements in solution in the outer core as it crystallizes to form the inner core. Enrichment of the fluid in light elements causes it to rise. The gravitational energy released is used to drive the convective motions at the origin of the gyrodynamo and is eventually transformed into heat by ohmic dissipation.

To understand the dynamics of the Earth, one therefore needs to investigate the physical processes that take place in its depths, especially at or near the core-mantle boundary (CMB for geophysicists). The CMB, which lies at a depth of 2900 km corresponding to a pressure of 1.35 Mbar, is a discontinuity defining contrasts in many ways as important as those between the solid Earth and the atmosphere or hydrosphere. Below lies the fluid core pervaded with magnetic field lines — a 2300 km-thick shell of an electrically conducting, molten iron alloy with a molecular viscosity close to that of water (a few centipoises) and a density of about 10 g/cm^3, flowing with velocities of the order of 1 metre per hour. Above lies, the very viscous (about 10^{22} Poise), less dense (5.6 g/cm^3) rock of the lower mantle, essentially constituted of a silicate of magnesium and iron and oxide phases found at high-pressure (both constituents are poor conductors of electricity). Seismology reveals a zone of irregular thickness (probably 200 km at most) and locally varying physical properties, the D" layer, lying just above the CMB at the base of the lower mantle.

It is here, at the top of the fluid core and the bottom of the lower mantle, that mechanical, thermal, electromagnetic, and chemical interactions take place between core and mantle and where, so to speak, most of the action occurs. It is therefore not surprising that this region of the Earth is the object of considerable attention on the part of geophysicists, who see it as a "new frontier". The International Union of Geodesy and Geophysics has recently created an interdisciplinary group called Study of the Earth's Deep Interior (SEDI), where seismologists, geomagneticians, mineral physicists, and specialists on the Earth's rotation join efforts to bring together information from each of their own fields by organizing and sponsoring symposia.

In what follows, I shall focus on core-mantle coupling and interactions, an exciting topic for which the physics of condensed matter at very high pressure plays an important role in analyzing many aspects. After briefly describing the variation of the Earth's rotation and the effect of core-mantle coupling, I shall consider the various coupling mechanisms and the contributions condensed matter physics makes in solving some of the problems which arise. In particular, I hope to show that condensed matter physics and experiments at very high pressures in a laser-heated diamond-anvil cell can add to our understanding of deep-Earth physics, and can significantly constrain the possible physical explanations of apparently remote astronomical problems such as perturbations of the Earth's rotation.

Length of the Day and Motion of the Poles

Astronomical determinations and precise measurements using very long baseline interferometry, using distant quasars, show that the angular velocity vector of a reference frame aligned with the principal axes of the solid Earth fluctuates slightly in time with respect to the inertial frame of fixed stars [1]. The fluctuations of the components of the angular velocity vector on the axes of the Earth-based frame correspond to variations of the angular velocity $\omega(t)$, *i.e.*, of the length of day (l.o.d.), and to motions of the rotation axis within the Earth.

The Earth's rotation velocity is decreasing steadily and the corresponding lengthening of the day is about 1.4 ms per century, mostly due to tidal interactions between the Earth and the moon: tidal friction causes the Earth's tidal bulge to remain at an angle with the line joining the centres of the planets so that it is subjected to a torque tending to slow down the Earth's rotation. Superimposed on this trend are short-period variations, of the order of a year and less, owing to angular momentum exchange between the atmosphere and the solid Earth.

Finally, fluctuations of the length of day (Fig. 1), with a period of about 10 years (decade fluctuations) and ranging in amplitude up to 5 ms, are attributed to angular momentum exchange between the fluid core and the rigid mantle. The liquid metal core is the seat of currents that generate the Earth's magnetic field; its flow exhibits

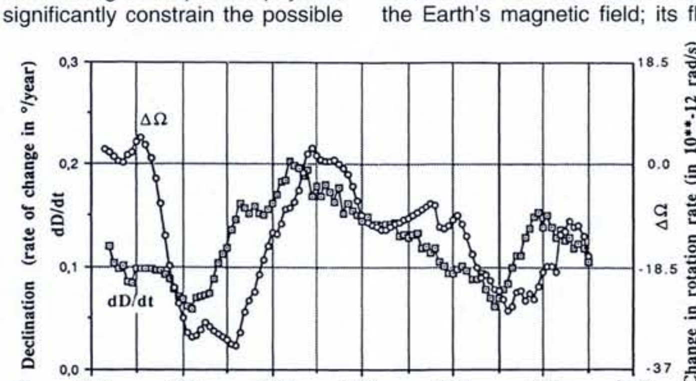

Fig. 1 — Changes in the Earth's rotation rate (circles) and secular variation of magnetic declination at the French National Magnetic Observatory. Sharp changes of slope in the variation of declination (jerks) around 1900, 1923, 1969 and 1978 are followed 9 ± 2 years later by sharp changes in the slope of the change of the Earth's rotation rate. The most recent change in the Earth's rotation rate was predicted in 1981 on the basis of the 1978 jerk [2].

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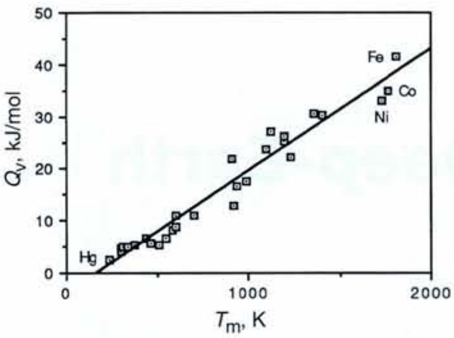

Fig. 2 — Correlation between the apparent activation energy for viscosity near the melting point (Q_v) and melting temperature (T_m) for 27 metals (from left to right: Hg, Cs, Ga, Rb, K, Na, In, Li, Sn, Bi, Tl, Cd, Pb, Zn, Sb, Pu, Al, Ba, Yb, Ca, La, Ag, Cu, U, Ni, Co, Fe). The apparent activation energy is nearly proportional to the melting temperature, leading to the conclusion that the viscosity at the melting point does not change when the melting point increases with pressure.

irregularities which result in the secular variation of the magnetic field, as observed at the Earth's surface. The correlation between core motions and variations of the length of day is seen in Fig. 1: accelerations or decelerations of the Earth's rotation rate seem to lag systematically by about nine years behind impulsions (jerks) in the secular variation of the magnetic declination [2].

Core-Mantle Coupling

As angular momentum is transferred from the core to the mantle, the rate of change with time of the angular momentum of the core is equal to the torque acting on the core-mantle boundary. Stresses on the CMB exerted by the core may have various origins:

i) viscous stresses in the thin boundary layer in the fluid core, below the CMB;

ii) stresses associated with Lorentz forces due to the interaction of the magnetic field with electrical currents induced in the weakly conducting lower mantle;

iii) stresses produced by the dynamical fluid pressure acting on the topographic irregularities ("bumps" of the order of 1 km) of the CMB.

To find out which mechanisms of core-mantle coupling are active, one must estimate the values of the different kinds of stresses and check whether they can produce a torque large enough to account for the rate of change of angular momentum of the mantle. It is clear that the viscosity of the core and the electrical conductivity of the lower mantle and the D" layer must be known, or at least estimated, hence the contribution of high-pressure physics.

Viscosity of the Core

The study of the secular variation of the magnetic field observed at the Earth's surface has led geomagneticians to infer a velocity of about 1 m/h for the fluid currents at the top of the core. The viscosity of the core is thought to be very small and the viscosity term in the Navier-Stokes equation is usually neglected before the Coriolis term. It is therefore of interest to investigate whether this assumption has any physical basis.

There is as yet no generally accepted theory of the physics of the viscosity of liquids, but there are experimental data on the viscosity of liquid metals near their melting points. Although there is no unassailable reason for interpreting the data in terms of a theory of thermally activated processes, they generally fit rather well an empirical Arrhenius law [3]:

$$\eta = \eta_0 \exp(-Q_v/RT)$$

where η is the viscosity, R is the gas constant and Q_v is the apparent activation energy which depends linearly on the melting temperature T_m (Fig. 2) such that $Q_v \approx 3\,RT_m$. It is then obvious that the viscosity of a liquid metal at its melting point does not depend on T_m and will always be the same at all pressures. So the viscosity of the liquid core at the pressure of the inner core boundary (where the liquid freezes onto the solid inner core) is about equal to that of the liquid iron at its melting point under atmospheric pressure (*i.e.*, $\eta \approx 6 \times 10^{-2}$ Poise), hardly more than the viscosity of water at room temperature and pressure. With a density of the core equal to 10 g/cm^3, the kinematic viscosity ν of the core near the core-mantle boundary (at $T>T_m$) must be about 4×10^{-3} cm^2/s, which is much too small to be of any importance in core-mantle coupling.

It must, however, be noted that we are dealing here with the molecular viscosity; now, the fluid motions in the core are likely to be turbulent, so the eddy viscosity corresponding to transport of momentum by eddies may have to be taken into account. Eddy viscosity is usually many orders of magnitude larger than molecular viscosity; it has been suggested that it is of the same order of magnitude as the magnetic diffusivity of the core if the energy of eddies is dissipated by magnetic friction: $\nu_E \approx \mu \approx 10^4$ cm^2/s. It would then be about six orders of magnitude larger than molecular viscosity so some viscous coupling between core and mantle should be taken into account. Eddy viscosity has also been invoked to account for the discrepancy between the observed and calculated values of the period of the free-core nutation, *i.e.*, the motion of the Earth's rotation axis due to fluid pressure imbalance on the spheroidal core-mantle boundary [4].

Electrical Conductivity of the Lower Mantle

The electromagnetic torque acting on the mantle is equal to the sum of the moments of the Lorentz forces acting on the material pervaded by electric currents induced in the weakly conducting lower mantle. It therefore depends on the electrical conductivity profile $\sigma(z)$ as a function of the depth z in the lower mantle. Conductivity profiles can be obtained from long-period magnetotelluric data (using variations of the external magnetic field) extending from the Earth's surface down to depths of about 1500 km. This depth still corresponds to 1400 km above the CMB so only an upper limit of the conductivity near the core-mantle boundary can be obtained from secular variation data. It is therefore necessary to resort to laboratory measurements of the variation of the electrical conductivity of the mantle material with temperature and pressure to constrain the conductivity profile of the lower mantle.

There is every reason to believe that the lower mantle is constituted of a mixture of about 40 volume % of magnesiowüstite (Mg, Fe)O and 60% of the high-pressure silicate (Mg, Fe)SiO_3 with 6-fold coordinated silicon in the dense perovskite structure. These contituents result from the transformation at the depth of 660 km of the major phases of the upper mantle, namely olivine (Mg, Fe)$_2SiO_4$ and pyroxene (Mg, Fe)SiO_3 which both have about 10 atom % Fe [5]. The transformation can be reproduced in laser-heated diamond-anvil cells, at pressures higher than about 230 kbar.

The electrical conductivity of the lower mantle material has been estimated using measurements made in a diamond-anvil cell [6] at high pressures (up to 400 kbar, corresponding to a depth of about 1000 km) of small samples (Fig. 3) of the high-pressure assemblage transformed from olivines with various iron contents. The temperature (up to 400 °C) was obtained by means of a small heater around the diamond avvils. The effects of temperature and pressure were investigated and the data, together with the temperature and pressure profiles as a function of depth in the Earth, allow a reasonable extrapolation down to the depth of the core-mantle boundary. The experiments also give information on the physical mechanisms responsible for the conductivity of the mantle. The electrical conductivity is thermally activated and its measured temperature and pressure P dependence is expressed by an Arrhenius law:

$$\sigma = \sigma_0 \exp[-(\Delta H + P\Delta V/RT)]$$

Recent results for an assemblage with 11 at.% Fe give an activation energy $\Delta H \approx$ 0.4 eV and a negative activation volume ΔV = -0.2 cm^3/mol. Conductivity therefore increases rather slowly with temperature: it also increases with pressure and with iron

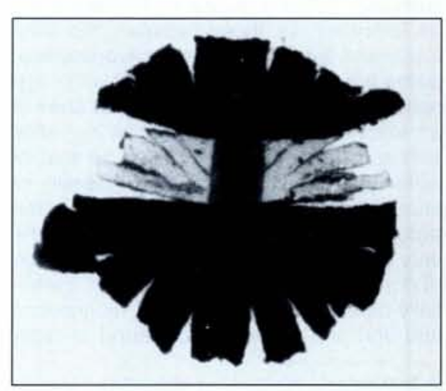

Fig. 3 — Electrical conductivity sample recovered from the diamond-anvil cell. The black areas (top and bottom) are tungsten ribbons, playing the role of electrical leads and confining gasket. Olivine powder, between the leads, is pressurized to 400 kbar and the laser beam is rastered vertically, producing the sample of transformed perovskite-magnesiowüstite, 80 mm wide (dark stripe). The sample is embedded in untransformed, electrically insulating, olivine (clear). The radial cracks were produced during decompression.

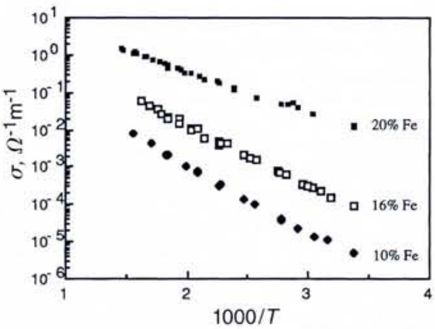

Fig. 4 — Arrhenius plot of the logarithm of electrical conductivity σ (in $\Omega^{-1}m^{-1}$) versus the inverse of absolute temperature (betwen room temperature and 673 K), for perovskite-magnesiowüstite assemblages prepared from natural olivines with various iron contents (in atom percent) at 400 kbar. The slope of the lines is proportional to the activation energy (about 0.4 eV). Electrical conductivity increases and activation energy decreases with iron content.

content (Fig. 4). These results are incompatible with ionic conduction and can be accounted for by a conduction mechanism involving the hopping of small polarons in magnesiowüstite:

$$Fe^{2+} \rightarrow Fe^{3+} + e^-$$

The small, negative activation volume compares well with the difference in ionic volumes between Fe^{3+} and Fe^{2+} involved in the creation of Fe^{3+} as a charge carrier.

Extrapolation to the temperature and pressure at the base of the lower mantle yields an electrical conductivity of the order of 1 to 10 $\Omega^{-1}m^{-1}$, in reasonable agreement with the geomagnetic estimations. A conductivity profile in the lower mantle consistent with these values does not lead to an electromagnetic torque strong enough to account for the observed decade variations in the length of day [7]. However, electromagnetic coupling cannot be entirely ruled out because the electrical conductivity of the still somewhat mysterious thin D" layer, found immediately above the core-mantle boundary, might be different and possibly higher than that of the lower mantle.

Constitution of the D" layer

The D" layer is laterally heterogeneous: seismic velocities vary by a few percent on the scale of a few hundred kilometres. The variation is too large to be explained by heterogeneities in temperature and it is believed that it can arise from compositional variations.

In an attempt to "simulate" the core-mantle boundary [8], it was recently shown that, in the laser-heated diamond cell at pressures above 700 kbar, iron reacted with perovskite and magnesiowüstite and that it dissolved oxygen from these oxides. It was then suggested that some iron may be drawn by infiltration from the core into the base of the lower mantle, and that heterogeneous accumulation of the reaction products constitutes the D" layer. The infiltrated material (iron and iron oxides) have about the same electrical conductivity as the core ($\sigma \approx 10^6\ \Omega^{-1}m^{-1}$) and it was proposed that the heterogeneities would pin the magnetic field lines and perturb the secular variation field observed at the Earth's surface [8]. On the basis of these experiments, other authors have assumed that a thin infiltrated layer could have the same conductivity as the core and cause electromagnetic dissipation, thus accounting for some of the discrepancies between calculations and observations of the damping of the forced tidal nutation of the Earth. The questions are therefore as follows: Is infiltration of fluid core material into the solid lower mantle possible? And if so, can it increase the electrical conductivity by six orders of magnitude, thus affecting the secular variation and causing magnetic dissipation and possibly core-mantle coupling?

The infiltration process has been investigated by pressurizing a mixture of iron and olivine in the diamond-anvil cell (at pressures up to the pressure of the CMB), heating it with a laser so that the iron melts, and observing the recovered sample using analytical transmission electron microscopy [9]. Iron veins are clearly seen at grain boundaries between oxide grains depleted in iron (Fig. 5), thus confirming that infiltration is possible at the scale of grains and that iron dissolves iron oxide from magnesiowüstite and perovskite under pressure. It can be shown semi-quantitatively [10] that iron with oxygen in solution is indeed able to corrode and wet the grain boundaries and infiltrate up to the height of the capillary rise (of the order of tens of metres) in short times (of the order of the year). If it is assumed that the infiltrated zone is swept up by convection, pervading the D" layer with electrically conducting core fluid; the fluid fraction can be roughly constrained by the seimic velocity decrease and is found to be probably less than 1%. This decrease is much too low to significantly increase the conductivity of the D" layer above that of the mantle and account for electromagnetic coupling, let alone perturb the magnetic field observed at the Earth's surface [10].

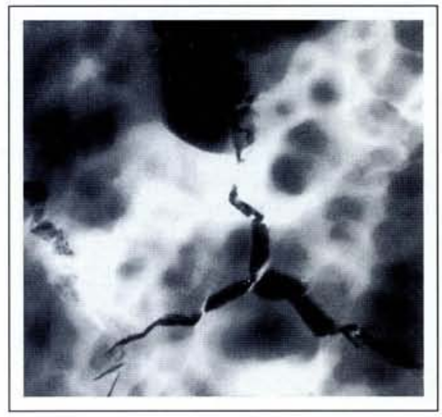

Fig. 5 — Infiltration of molten iron (dark) wetting grain boundaries of silicate perovskite. Infiltration of iron from the core into the lower mantle can happen at the core-mantle boundary. Transmission electron micrograph of a sample prepared at 700 kbar. Magnification: 10 mm = 0.5 μm.

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