HEAT FLOW ACROSS THE CORE-MANTLE BOUNDARY

The boundary between the core and the mantle is of huge importance for the dynamics of the Earth's interior and the seat of many interesting phenomena (see Core-mantle Boundary and Core-mantle coupling, thermal). From the core point of view this is the surface across which all heat produced must escape. The value of the integrated heat flow across the core mantle boundary (CMB) is then of primary importance for the thermal evolution of the core and it controls the amplitude of the energy sources available to drive the geodynamo (see Energy sources for the geodynamo).

All the energy that flows out of the core must be transported upward across the mantle. The mantle is primarily solid (except in the very localised regions of partial melting) but it can creep and is subject to convective movements on time scales of some tens of millions of years (Myr), the surface expression of these motions being plate tectonics. On the other hand the outer core is liquid, with a viscosity close to that of water (See Viscosity of the core) and its dynamics is then much faster. The secular variation of the magnetic field suggests that the velocity in the fluid core is on the order of $10^{-4}\ \mathrm{m\,s^{-1}}$ (e.g. Hulot et al., 2002) which, together with the radius of the core $3.48\ 10^6\ \mathrm{m}$, gives a typical time scale of about a thousand years.

The mantle being much more sluggish than the core, it constitutes the limiting factor for the thermal evolution of the Earth and the heat flow across the CMB is the heat flow that mantle convection can accept. Of course, the state of the core affects this value by imposing a temperature difference between the bottom and the top surfaces of the mantle, that is, in non-dimensional units, a Rayleigh number for the mantle. Both systems are then coupled in their evolution.

Total heat loss of the core

Energy balance of the mantle

The heat flow across the CMB is controlled by mantle convection and gross estimates of its integrated value can be obtained by use of the global energy balance of the mantle. This balance states very simply that the heat flow at the surface of the Earth is, to first approximation, equal to the sum of three terms: The heat production by decay of radioactive elements in the mantle, the cooling heat associated with the heat capacity of the mantle (this term is called secular cooling of the mantle) and the heat flow across the CMB. The latter of these terms should then be obtained by simple difference, providing all others can be determined accurately. We will see here that this approach can give reasonable estimates but hardly any precise value.

Other energies are involved in the thermodynamics of mantle convection but they are either negligible or internally balanced. Among the first group, one can cite tidal friction (Verhoogen, 1980), latent heat due to the secular movement of phase boundaries upon mantle cooling and adiabatic heating from slow contraction. Another energy term which is often discussed, viscous dissipation, can be locally important but does not enter the global energy balance because it is internally balanced by the work of buoyancy forces (as is the case for the core: see Energy sources for the geodynamo and Hewitt et al. (1975)). Gravitational energy due to chemical stratification was a very important source of energy during the formation of the core (Stevenson, 1981), early in Earth history, but is likely gone by now. Similar processes like the formation of the continental crust or opposite ones like the slow mixing of a primordial chemical stratification (Davaille, 1999) could still be at work but are likely negligible due to the small masses involved.

The total heat loss of the Earth is reasonably well known to be about 42 TW from heat flux measurements made both on oceans and continents, as well as interpolation based on models for the cooling of oceanic plates (Sclater et al., 1980). The value of total heat production by radioactive decay relies on cosmochemical models for the formation of the Earth, or more precisely on the choice of meteorites that is supposed to have formed the Earth. Most models assume a CI carbonaceous chondrite origin for the Earth, leading to a total heat production in the silicate Earth (mantle plus crust) of about 20 TW (see Javoy, 1999, for a critical discussion). The distribution of the heat producing isotopes (^{40}K, ^{235}U, ^{238}U, ^{232}Th) in the Earth is clearly non uniform, the continental crust being largely enriched compared to the mantle, but this matter does not affect the estimates presented here as long as the heat flow at the surface is considered. The secular cooling term is the least well constrained of all terms but we can already see that, unless the mantle is actually heating up, the heat flow across the CMB cannot be greater than $22\ \mathrm{TW}$, a value obtained in the case of a steady mantle temperature.

To get a more useful upper bound one needs a model of thermal evolution of the mantle. Unfortunately, our understanding of mantle convection is still far from complete and no entirely satisfying model of mantle cooling is available at present. In particular, these models usually predict a very fast cooling of the Earth in the early stages of the evolution so that they cannot maintain the present surface heat flow with the concentration in radioactive elements estimated from geochemistry (e.g. Grigné and Labrosse, 2001). Nevertheless, these models all predict present day rate of mantle cooling between 50 and $100\ \mathrm{K\ Ga^{-1}}$ (e.g. Schubert et al., 2001) which is similar to estimates based on the chemistry of basalts (e.g. Abbott et al., 1994). Using a heat capacity of about $10^3\ \mathrm{J\ kg^{-1}\ K^{-1}}$ and a mass of the mantle of $4\ 10^{24}\ \mathrm{kg}$, this gives a contribution of secular cooling of about 6 to $12\ \mathrm{TW}$ to the heat flow at the surface. Subtracting this value to the $22\ \mathrm{TW}$ estimated above, a heat flow across the CMB of 10 to $16\ \mathrm{TW}$ is obtained. Considering the very approximate nature of this estimate, it should only be taken as a crude but plausible range.

A mechanical point of view

Alternatively to looking at the global balance of the mantle and modeling its temporal evolution, the heat flow at the CMB has been estimated by computing the buoyancy flux of the differents mantle hot plumes that are supposed to be responsible for the formation of hotspot tracks, such as Hawaii. Using different hotspot catalogues, values around $3\ \mathrm{TW}$ for the total heat coming out of hotspots have been typically obtained (Davies, 1988) and this value has been often quoted as the total heat loss of the core. The idea behind that estimate is that all the heat that comes out of the core is collected in the boundary layer at the bottom of the mantle and transported upward to the surface by mantle plumes, the surface expressions being hotspots.

The value obtained is low compared to the range given previously but could be acceptable (considering the approximate nature of this range), although the reasoning used to get it is questionable. Without even entering the long standing debate regarding the origin of hotspots, two issues regarding the link between the heat transported to the surface by hot mantle plumes and the total heat loss of the core can be raised, both coming from the difficulty of considering any particular dynamical object as a separate entity in a convective flow. First, it is difficult to imagine that hot plumes move straight up from the boundary layer where they originate to the surface without any effect of the large scale mantle circulation associated with plates. Several models actually show that many (if not most of) hot plumes that form at the bottom of a convective system containing some important ingredients of mantle convection such as temperature dependent viscosity, volumetric (radiogenic) heating and large (plate size) scale flow do not rise to the surface (Labrosse, 2002).

Second, there are two modes of cooling of the core, both operating simultaneously. You can take some hot matter and move it upward in the form of plumes or take some cold matter from the surface and spread it on top of the core. This separation is a little arbitrary since in both cases you replace some hot matter by some cold matter, but, in the former, this matter comes from the ambient mantle whereas in the latter it comes from the surface, in the form of plates. The relative importance of these two modes depends on both the mass flux of cold matter brought to the boundary and the temperature difference involved. Both these parameters are more important for the cold down welling currents than for the hot up welling plumes in convection models that include volumetric heating (Labrosse, 2002) and it is easy to think that this difference will be even larger in the case of the mantle, where cold plates represent the dominant feature of lateral heterogeneities. This means that a better estimate of the heat flow across the CMB could be obtained if the mass flux associated with plates were known in the lower mantle. This is unfortunately not the case and no estimate better than the one proposed using the gross energy balance above seems possible for the time being.

Estimates from the core side

Even though mantle convection controls the heat flow across the core mantle boundary, the fact that a dynamo has been operating in the core for most of its history places constraints on this value: It must be large enough to maintain the dynamo action. The thermodynamics of a convective geodynamo has been studied by several authors (see Energy sources for the geodynamo) and the results will be shortly recalled here.

The decay time of the dipole of the Earth is of the order of 15kyr (see Time scales and dimensional analysis), that is much smaller than the age of the Earth magnetic field, which means that a dynamo action must be regenerating it against ohmic dissipation. A particularity of the thermodynamics of convective flows, compared to the classical Carnot engine, is that the work is performed inside the system so that the energy balance only states the equilibrium between the sum of heat sources and the total heat loss, the heat flow across the CMB in the case of interest here. On the other hand, an entropy balance can be used to relate the total ohmic dissipation in the core to the energy sources that drive the dynamo, with the introduction of some "efficiency factors". Several combinations of different energy sources are possible, particularly depending whether one think that radioactive elements are present in the core or not, and added to the uncertainties attached to most physical parameters, a total heat flow across the CMB in the range of 5 to 15 TW can be predicted for a total ohmic dissipation in the core of about 1 to 2 TW. It must be noted that the uncertainty in this total ohmic dissipation is probably the largest in the whole set of parameters of this type of derivation, owing to our current lack of knowledge concerning an important part of the magnetic field in the core, the toroidal and the small scale poloidal part.

The estimates discussed above fall in about the same range as those obtained previously from the mantle side, which can be taken as a good sign, but it means that it does not really help in narrowing down this range. Another point of comparison is provided by the average adiabatic temperature gradient in the core, along which about 7 TW is conducted. If the actual heat flow is lower than this value, a stable thermal stratification would tend to be established at the top of the core (see Subadiabatic temperature gradients).

Lateral variations

In addition to the value of the total heat flow across the CMB, the amount and scale of lateral variations of the heat flux may be of equal importance for the dynamics of the core. These lateral variations are imposed by mantle convection and evolve on time scales much longer than those associated with the dynamo. These variations can then be seen as a permanent inhomogeneous boundary condition imposed on the core by the mantle, the effects of which being still not completely understood (see Inhomogeneous boundary conditions and the dynamo).

Convection being responsible for the heterogeneities in seismic velocities at the bottom of the mantle, it is tempting to use the images of these heterogeneities as produced by seismic tomography to convert them to maps of lateral variations of the heat flux at the CMB. This assumes that all the lateral variations in seismic velocities are of thermal origin and that a single, so-called, conversion factor can be used for the operation. On the other hand, there is some evidence for non-

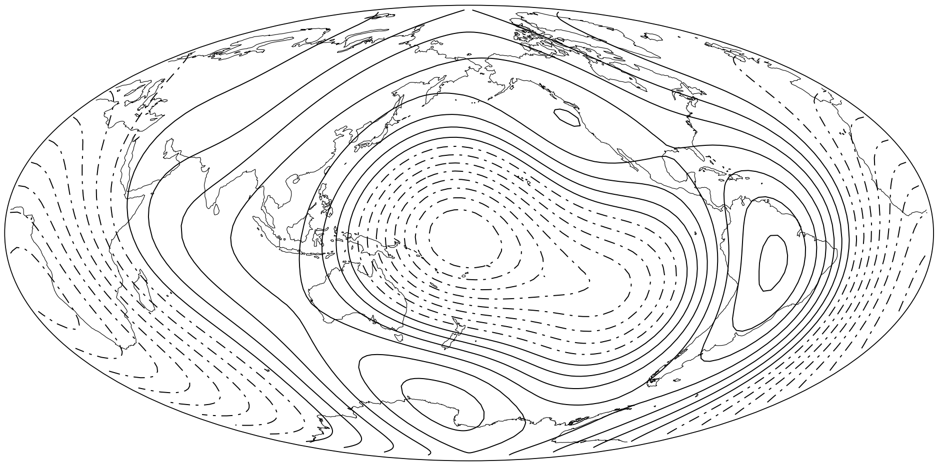

Figure 1: Pattern of heat flux lateral variations at the core mantle boundary in the so-called ”tomographic” model of Christensen and Olson (2003). Heat flux higher than averaged is in plain contours and correlate well with the position of subduction zones at the surface. Reproduced by permission of U. Christensen and P. Olson and Elsevier.

purely thermal origin of these heterogeneities, in which case the chemical part of the signal must first be separated, a still formidable task. Several studies about the effect of heterogeneous boundary conditions on core dynamics (e.g. Glatzmaier et al., 1999; Olson and Christensen, 2002) have nevertheless assumed a purely thermal origin of the lateral variation of the seismic velocities and the heat flux pattern obtained is often called the “tomographic heat flux”, the amplitude of the lateral variations remaining a largely unknown adjustable parameter. This pattern is essentially controlled by the large scale structure of tomographic images and, in particular, features a large heat flux ring falling bellow the subduction zones around the Pacific Ocean (fig. 1). This can be optimistically taken as a sign of consistency since the subducting plates, if they reach the bottom of the mantle, will produce a high heat flux.

There is no direct measurement of the amplitude of the lateral variations of heat flux at the CMB, but some argument can be made about their being quite large. First, the contrast between the core and the mantle is as important as the one between the mantle and the ocean, so that variations of the same relative importance can be expected at the CMB than at the surface. The existence of crypto-continents at the CMB has even been proposed (e.g. Stacey, 1991), and such could be the name given to the piles of chemically dense material that are envisioned in some models of mantle convection with chemical heterogeneities (e.g. Tackley, 1998; Davaille, 1999). At the Earth surface, the mean heat flux through oceanic plates is about $100\ \mathrm{mW\,m^{-2}}$, with a pic-to-pic variation equal to this value (Sclater et al., 1980), and it is reasonable to assume that variations of the same relative amplitude exist at the CMB. One can even defend the case of larger variations, owing to the fact that these variations are controlled by the effect of down welling plates which are associated with the lateral variations of the heat flux at the surface. One can for example construct a mantle convection model driven by internal heating and a top surface maintained at a low temperature with a zero net heat flow at the bottom surface, although displaying lateral variations of a quite large amplitude. Pic-to-pic variations of the heat flux at the core mantle boundary of the same order as the mean value present then a conceivable picture.

The possibility of thermal stratification that was mentioned above has to be discussed again in the context of the lateral variations of the heat flux at the CMB. Considering the likely importance of these variations, and the closeness of the estimates of the actual heat flux at the CMB and of that conducted down the adiabatic temperature gradient, it is likely that some regions of the CMB present a stable thermal stratification. The effects of such patches on the dynamics of the core and the generation of the magnetic field are still largely unknown but have to be investigated.

Variations with time

The heat flux across the CMB is not only varying laterally but also with time, on the time scale of mantle convection. Moreover, the pattern of lateral variations is also evolving on the same time scales and both temporal evolutions are likely to be of great importance to understand the long term variations of the magnetic field. Unfortunately, the knowledge that one can get for the time evolution of the heat flow across the CMB is even scarcer than about the present day value. In particular, most of what we know about the present heat loss of the Earth comes from the study of the seafloor (Sclater et al., 1980), which is not older than about $200\ \mathrm{Ma}$. However, one can put forward the argument that some ergodicity holds so that the variations of this heat loss with time can be as large as the lateral variations observed at the present day. Most of the heat loss of the Earth comes from the formation of mid-oceanic ridges and the heat budget of the Earth can be considerably changed by modifying the number of active ridges, or equivalently the average size of mantle convection cells. For example, the Atlantic ocean is responsible for about 6 TW of the 30 TW of total oceanic heat flow and it opened between 180 and 120 Myr ago. Before that time, if no other ridge of equivalent importance was active, the heat loss of the Earth must have been 6 TW lower than at present.

From the previous discussion, one can easily imagine (although not prove) variations of the total heat loss of the Earth of the order of 10 TW on time scales of about 200 Myr (Grigné et al., 2005). As for the heat flow across the CMB, it is likely to have undergone variations on a similar time scale, with amplitudes that could be as large as the amplitude of the present day lateral variation, which, unfortunately, is poorly known as discussed above. This means that important variations of the ohmic dissipation in the core must have occurred (see Energy sources for the geodynamo) and understanding the link between these variations and the variations of the magnetic field characteristics would provide a mean of investigating this evolution.

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Cross references

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