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The potential influence of radiative heat transfer on the formation of megaplumes in the lower mantle

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Abstract

Recent seismic tomographic models have revealed broad, low-velocity anomalies in the lower mantle beneath Africa and the central Pacific which suggest a break in the symmetry between hot and cold regions in lower mantle dynamics. We have considered the possible impact from radiative heat transfer, which can be described by a nonlinear temperature-dependent coefficient in the thermal conductivity, in 2D numerical simulations. Results for Rayleigh numbers up to 10^6 show a strong stabilizing influence from radiative heat transfer on mantle upwellings and the production of extremely hot thermal anomalies in the interior. This nonlinearity is responsible for producing a strong attractor in the mantle convective system, which greatly simplifies its time-dependent dynamics. The possible link of the simplified lower mantle time-dependent dynamics with polar wander is discussed. The main point here is that slow time dependence of the huge anomalies in the lower mantle can be the main mechanism controlling long-term rotational dynamics.

1. Introduction

Seismic tomography has revealed broad blob-like low S-wave velocity anomalies (megaplumes) in the lower mantle under Africa and the central Pacific [1–4]. We have converted these into thermal anomalies employing recent mineral physics measurements [5–7] and we present the 3D thermal images of both megaplumes in Fig. 1. The dominating effect here is the broadening of hot anomalies near the core–mantle boundary (CMB). It is of interest that both megaplumes have two cores each, which suggests some kind of megaplume internal dynamics. The detailed review of P-wave tomography by Fukao et al. [8] also revealed these two megaplumes and confirmed their origin from the D″ layer. They do, however, exhibit more complicated structures by both necking in the mid-lower mantle and branching towards the 670 km discontinuity. Recently the extension of these large structures to the upper mantle beneath the same geographical locations has been found by Romanowicz [9] using the 3D distribution of seismic attenuation. All

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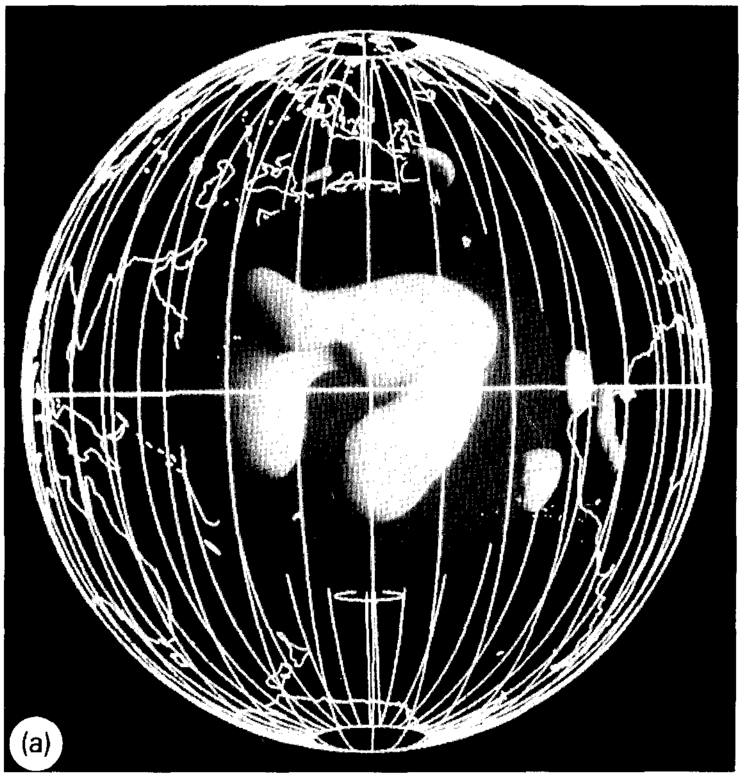
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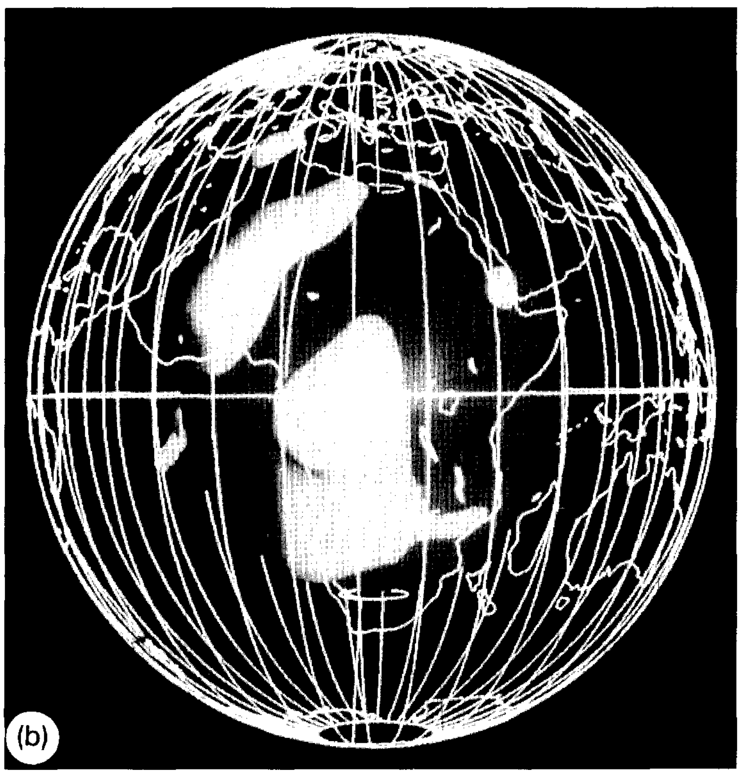

(b)

of these seismic data show the overall presence of the megaplumes in the mantle, which possess a symmetry that must result from some underlying physical mechanism [10]. Some sort of bipolar symmetry reflecting the surface correspondence of the Pacific and African plates is known also from the studies of various surface geophysical fields:

Pavoni [11] introduced the geotectonic reference network defined by the Pacific Pole at 170°W/0°N and the African Pole at 10°E/0°N. The Circum-Pacific Ring as well as the Circum-African Ring form latitudinal small circles with respect to this network. Moreover, Rykunov [12] noticed that the same direction corresponds to the main equatorial bulge of the non-hydrostatic geoid and to the centres of the hemispheres of maximum and minimum heat flow. After removing the geoid generated by the subducting slabs, the residual geoid highs are related to the Pacific and African hotspot groups [13].

Matyska's detailed study [14] of the angular symmetries of hotspot distributions confirmed that the 180° rotation symmetry is of great importance in this regard because it can be found for almost all axes lying in the plane roughly given by the meridians 120°E/60°W. This means that the hotspot distribution is partly axisymmetrical with respect to the axis perpendicular to this plane and hence deviates only 20° from Pavoni's axis. The connection between the bipolar symmetry of the hotspot distribution and the megaplumes was demonstrated by Kedar et al. [15] who found very good correlation between the hotspots and slow

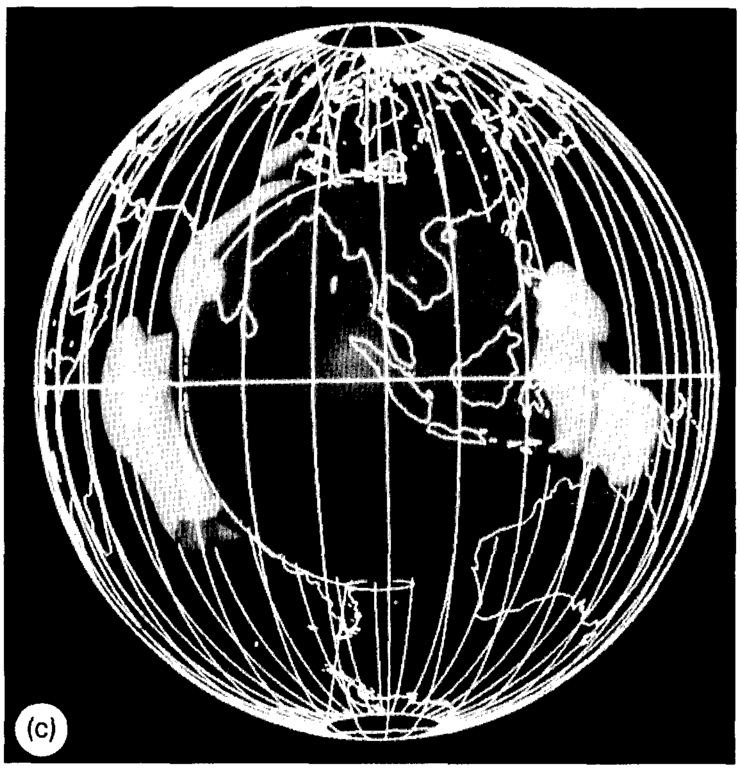


Fig. 1. Isosurfaces of non-dimensionalized temperature variations $(\partial \ln\rho/\alpha\partial\ln v_S)_z(\alpha\partial\ln v S/\partial\ln\rho)_{670}(\delta v_S/v_S) = -0.03$, where z denotes depth (km), for the model SH425.2 of Su and Dziewonski [1] of S-wave velocity variations. The non-dimensionalised conversion parameter standing at $(\delta v_S/v_S)$ increases approximately linearly with increasing depth and is roughly equal to 4 at the CMB [7]. (a) The Pacific megaplume. (b) The African megaplume. (c) View from the Indian Ocean.

regions of shear waves [4] in degree 2, and only degree 2, in the bottom half of the lower mantle. Moreover, Rampino and Caldera [16] showed that significantly more hotspots occur as nearly antipodal pairs than is anticipated from a random distribution. The possible explanation of all these correlations was presented by Richards et al. [17], who hypothesized that hotspot plumes are preferrably formed in broad hot lower mantle regions. The highs of the geoid are, consequently, the results of surface dynamic topography generated by the plumes. This idea has been indirectly confirmed by Yuen et al. [7], who obtained the thermal structures of the Pacific and African megaplumes from seismic results by means of recent mineral physics data and found that the thermal anomalies can exceed several hundred degrees. Fig. 1 has been constructed graphically using the same mineral physics constraints as in [7] and the tomographic model SH425.2 of Su and Dziewonski [1].

The relationship between mantle dynamics and the real surface topography is, however, complicated because the surface topography is influenced mainly by shallow heterogeneities. Nevertheless, an anomalous region of seafloor in French Polynesia, which is not far from the Pacific Pole, has been found and named the Superswell [18,19]. Moreover, Cazenave et al. [20] have shown that the global surface topography corrected for shallow density variations inside the lithosphere presents a strong degree 2 pattern of the spherical harmonic expansion with the maximum highs on the equator at 0°W and 180°W. There is a good correlation with the degree 2 pattern of the nonhydrostatic geoid and of the hotspot distribution. However, this correction of the topography was questioned by Colin and Fleitout [21] who argued that an incorrect age law for the topography of the cooling oceanic lithosphere was used.

These recent geophysical inferences of megaplumes in the lower mantle and the relatively low amplitude of the seismic spectra with respect to the upper mantle [1,2,10] truely beg for some sort of physical explanation. Clearly they cannot be explained with the proverbial constant viscosity convection models. These constant viscosity models produce symmetrical [22] strongly time-dependent instabilities of hot and cold origins [23]. We need physical mechanisms which break these symmetries. Potentially possible mechanism must be able to acount for the broadening of hot regions. Certainly temperature-dependent viscosity cannot fit the bill since it results in upwelling sheets and downwelling plumes [24]. We rather need some diffusive mechanism, which has strong temperature-dependence as a feedback. This qualification suggests that radiative heat transfer may be a very good candidate for this purpose.

Radiative heat transfer can be taken into account by introducing the thermal conductivity dependent on the cube of the absolute temperature [25]. The total thermal conductivity then consists of the two terms lattice conductivity and radiative conductivity. Because of the temperature-cubed dependence, the radiative conductivity can increase substantially in the lowermost mantle, especially in D″ which, from the point of view of dynamic models, plays the role of the lower boundary layer with the bottom temperature 4000 ± 200 K according to the newest static measurements of the iron melting point [26]. In contrast, radiative heat transfer decreases with increasing pressure [27] and may thus even decrease with depth in the upper mantle where the influence of pressure dominates. The increase in lattice conductivity with pressure and its decrease with temperature [28,29] approximately balance and that is why the lattice conductivity is not strongly depth dependent. Therefore, radiative and temperature-dependent thermal conductivity can be disregarded in the upper mantle, but they can dominate in the high-temperature regimes characteristic of the deep mantle.

In this study we have focused only on the effects of radiative heat-transfer and hence we have employed just the Boussinesq approximation and have not included the effects of compressibility. The principal aim of this study is to explore the possible consequences in the changes of the style of mantle convection with increasing values of radiative conductivity. These results will help to stimulate future laboratory measurements that use laser-heated diamond-anvil technology, as in the recent melting experiments of Zerr and Boehler [30].

2. Boussinesq approximation of mantle convection with radiative heat transfer

Radiative heat transfer was a physical mechanism invoked for heat transfer in the mantle in the days when mantle convection was still a novel idea and temperature models of the mantle were based only on heat conduction [28]. In the conditions of high temperature and pressure of the lower mantle, radiative heat transfer conditions have not been measured, except under conditions of unusually low pressure [31]. Thus the viability of this mechanism is still subject to experimental verification.

Basically, in solid bodies, a sizable fraction of the energy transfer at high temperatures may proceed via thermal radiation by means of photons. The opacity ϵ of the solid medium is defined by the decrease in the intensity, due to absorption and scattering, of a beam of elmg radiation passing through a thickness x of material:

$$I = I_0 \exp(-\epsilon x) \tag{1}$$

For mean free paths of radiation $1/\epsilon$, which are much smaller than the characteristic dimensions of the body, the role of radiative heat exchange can be taken into account by introducing the radiative conductivity

$$k_r = \frac{16 n^2 \sigma T'^3}{3\epsilon} \tag{2}$$

where n is the index of refraction, σ is the Stefan–Boltzman constant and T' is the absolute temperature (the proof can be found in [25]). Measurements of the temperature dependency of earth materials [31] show that the increase in k_r need not be so rapid as T^3, which was interpreted as the increase in ϵ with temperature.

The coefficient of the total thermal conductivity k thus consists of the two terms: $k = k_l + k_r$, where k_l denotes the lattice conductivity by means of phonons. We will use the expression for the thermal conductivity in the form

$$k = k_l\left[1 + \beta\left(\frac{T'_0}{\Delta T'} + \frac{T' - T'_0}{\Delta T'}\right)^3\right] \tag{3}$$

where T'_0 is the absolute temperature of Earth's surface and $\Delta T'$ is the temperature difference between the surface and the CMB. Since $T'_0 \ll \Delta T'$, $\beta \doteq k_r/k_l$ near the CMB. In Earth β is not constant because it describes the dependence of the radiative conductivity on n and ϵ but, as a first approximation, we will consider it as a free constant parameter in this study.

For the purpose of illustrating the basic physics, we will adopt a rather simple model consisting of a 2D rectangular box with an aspect ratio of 4 for simulating this potentially important process in mantle convection. The momentum and energy equations for incompressible, Boussinesq fluid with an infinite Prandtl number and a constant viscosity are

$$\nabla \cdot \mathbf{v} = 0 \tag{4}$$

$$\nabla^2 \mathbf{v} + Ra T \mathbf{e}_z - \nabla p = 0 \tag{5}$$

$$\frac{\partial T}{\partial t} = \nabla^2 T + \beta \nabla \cdot \left[(T_0 + T)^3 \nabla T\right] - \mathbf{v} \cdot \nabla T \tag{6}$$

where $\mathbf{v}$, T and T_0 are, respectively, dimensionless velocity, temperature and surface temperature, $Ra = \rho^2 c \alpha g d^3 \Delta T' / k_l \eta$ is the Rayleigh number (ρ is density, c is the heat capacity, α is the thermal expansivity, g is the acceleration due to gravity, d is the layer thickness and η is the viscosity), p is the pressure, t is the dimensionless time and $\mathbf{e}_z$ is the unit vector in the direction opposite to that of gravitational acceleration.

The nonlinear system (4)–(6) has been solved by imposing the following boundary conditions: all boundaries are impermeable and shear-stress-free. The temperature is fixed at the top ($T = 0$) and at the bottom ($T = 1$) and reflecting conditions have been used on the side walls. For the spatial variables, we have used the decomposition into the Fourier series to solve analytically the system (4)–(5) and to perform the differential operators in (6) in the spectral domain; the time stepping has been carried out with a second-order explicit Runge–Kutta scheme in the spatial domain. In other words, the Fourier coefficients of each velocity component are obtained by means of the multiplication of the corresponding temperature Fourier coefficients by numbers expressing the transfer function between the tempera-

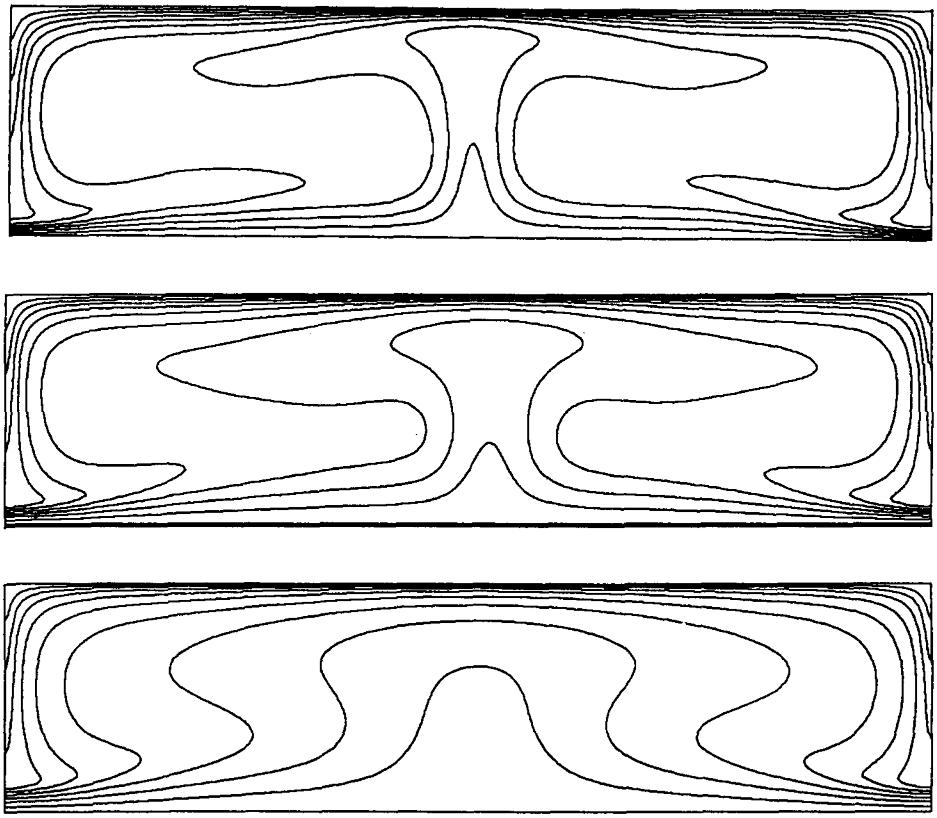


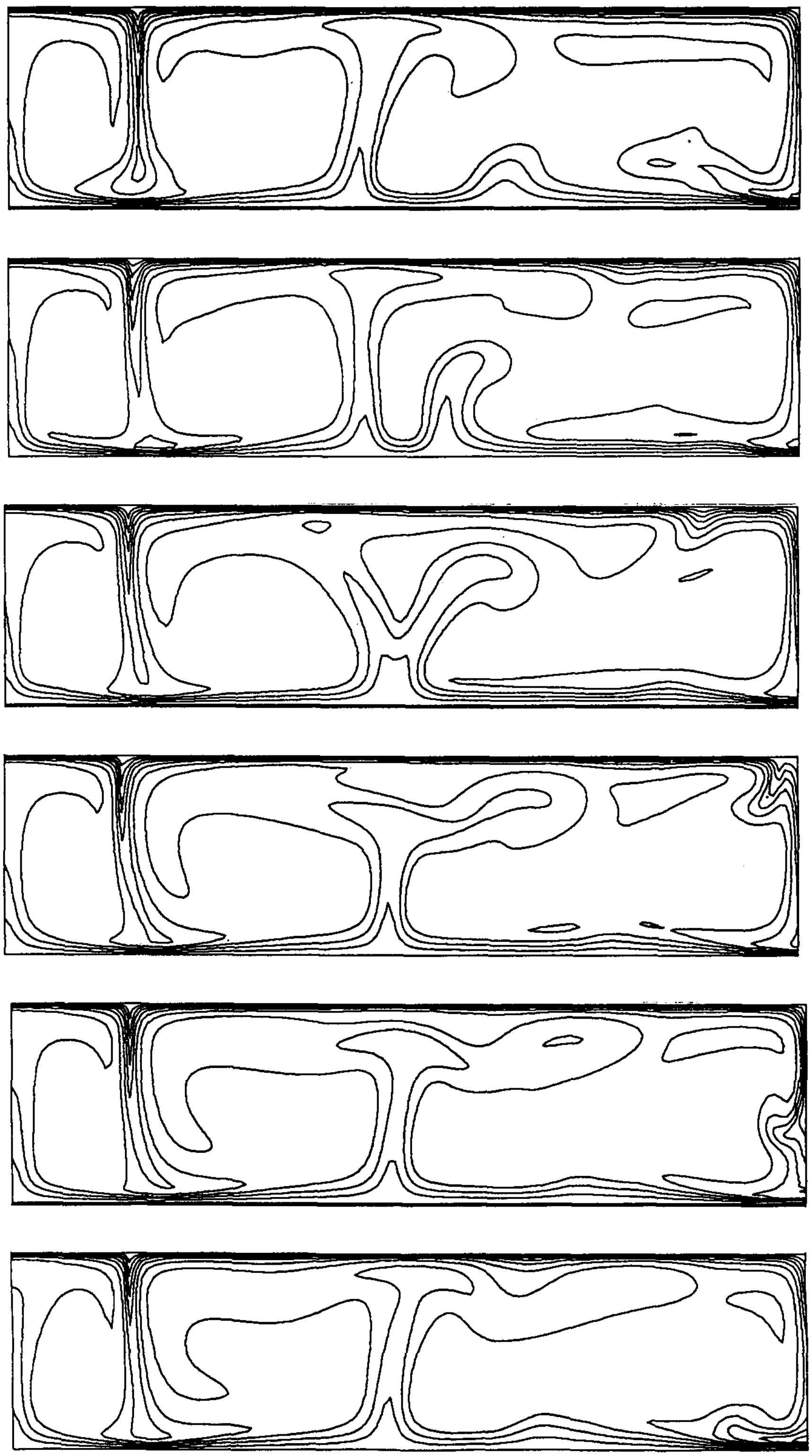
Fig. 2. Temperature attractors for $Ra = 10^5$. $T = 0$ at the top and $T = 1$ at the bottom. Contour interval is 0.1. Top: $\beta = 3$. Middle: $\beta = 10$. Bottom: $\beta = 30$.

ture and the velocity. The components of ∇T are obtained in an similar way. After the Fourier inversion all multiplications on the right-hand side of (6) can easily be performed in each grid point and the time step can be carried out. To fulfill the boundary conditions, we used the expansion of the function $T-(1-z)$ (z is the dimensionless distance from the lower boundary) into the cosine series in the horizontal direction up to degree 512 and into the sine series in the vertical direction up to degree 128. This corresponds to 257×65 grid points in the spatial domain.

3. Numerical simulations

There are two main consequences due to the presence of radiative heat transfer in thermal convection. First, it causes thickening of the lower boundary layer as well as hot plumes. Second, for large enough values of β an initially time-de-

Fig. 3. Snapshots of temperatures for $Ra = 10^6$ and $\beta = 10$. Contour interval is 0.1. The time step between the snaphots is approximately one-sixth of the overturn.



pendent solution without radiative transfer would become stable. In other words, there is a strong attractor in the solution space associated with large values of β, which causes an otherwise time-dependent solution to become locked onto a steady-state solution. This dynamic consequence due to the temperature-dependent property is quite novel and is in direct contrast to the effects of temperature-dependent viscosity, which provokes time-dependent behaviour.

Fig. 2 illustrates the stable, steady-state (strong attractor) solutions for $Ra = 10^5$, which were attained for $\beta = 3$, 10 and 30. These attractors are, however, associated with increasing velocities. The corresponding values of maximum vertical non-dimensional velocities are 580, 650 and 770 respectively. For comparison, we refer the reader to Fig. 1, where the megaplumes are shown. We must regard β here as a free parameter in this problem and we must study the physical consequences of changing β to obtain some understanding of the possible behaviour of real dynamics. From the methodological point of view, such an approach is similar to the way in which the more or less unknown activation energy was varied in mantle dynamics problems [32]. The classical compilation by Lubimova [28] suggested that β should not exceed 100 and that it is probably only of O(10) which, however, still means that the radiative heat transfer dominates near the CMB. As $\beta = 30$ completely stabilizes the convection for $Ra = 10^6$ but $\beta = 10$ does not, the lower mantle convection is likely to be slightly time dependent but far from turbulent solutions [23] which are typical of the simulations of higher Rayleigh number convection with no radiative heat transfer.

On the other hand, in time-dependent convection the push of a large, relatively stable plume is capable of enhancing plume–plume and mainly downwelling–downwelling collisions and thus of giving rise to flushing effects. In Fig. 3 the time-dependent dynamics of convection with radiative conductivity are shown. The plume–plume interactions culminate in the development of massive plumes with higher velocities than for lower values of β, but with bases much narrower than those of the stable solutions described above. The two cores of both observed megaplumes (see Fig. 1) might be the effect of plume–plume interactions. The merging of the cold descending flows gives rise to the rapid dropping of cold blobs into a relatively hot material, which produces lateral variations of temperature near the CMB with an astoundingly large amplitude of 80% of the total temperature drop across the mantle! This aspect is not found in ordinary convection without this strong nonlinearity of radiative transfer. This phenomenon may provide another contribution to the large lateral seismic anomalies obtained near the CMB [1,2]. This new phenomenon is obtained because of the nonlinearity present in radiative transfer and the high background mantle temperatures produced by the same physical mechanism. These two factors make the upwelling plumes as stable as they would be from depth-dependent properties [33–36], and may make them even stronger. This stabilization allows the simultaneous feeding of the mean flow by having the source of the transfer close to the lower boundary layer. Certainly this is not the only mechanism which can produce fast streams of cold material throughout the lower mantle, as endothermic phase transitions can also cause enormous gravitational instabilities, which are followed by similar flushing events [37–41]. Another important fact, which has not been considered in our simulations, is the very high melting temperature of perovskite [30]. Consequently, low homologous temperatures prevail in the lower mantle, which, therefore, will exhibit a sluggish, penetrative type of convection [42].

4. Consequences of the convection results on polar wandering

Recently there has been a resurgence of interest in the connection between mantle dynamics and polar wander [43–48]. The tendency of megaplumes to be formed by depth-dependent properties [33–36] and also by this particular mechanism of radiative transfer is certainly relevant to discussion on the role played by these megaplumes in controlling relatively slow polar movements of the order of 0.1°/Myr. The upward push exerted by the relatively stationary megaplume may be responsible for the large aspect-ratio cells and the bipolar character of the lower mantle. In other words, the long-wavelength nature of the seismic spectra of the lower mantle and its rapid spectral decay [1,2] suggest that some strong attractor, due to variations in physical properties, exists for lower mantle convection.

Convection dynamics are also connected to polar wander in a complicated nonlinear manner [46]. For this reason the lifetimes of megaplumes play an important role in these considerations. When the changes in the moment of inertia are slow, the rotational axis is almost identical with the maximum principal axis of the total moment of inertia [49]. This means that the off-diagonal elements of the total moment of the inertia tensor almost vanish in the reference system where the z-axis is defined by the axis of rotation. The off-diagonal elements generated by the source processes of mantle dynamics are compensated by the equatorial bulge delay, which is due to changes in the rotational axis [43–48]. Since the cause of the equatorial bulge delay lies in the viscous nature of Earth's rheology, its internal tendency is to diminish when polar wandering ceases. However, this is impossible without also simultaneously diminishing the off-diagonal elements of the moment of inertia due to the source density heterogeneities. In other words, the polar wander is the physical process which attempts to orient the rotational axis towards the principal axis of the density anomalies generated by the convective dynamics. This then is the reason why the rotational axis is the preferred axis for the convection pattern, as has already been advocated by Stevenson [50].

The next question arises: Do the megaplumes control the position of Earth's rotational axis?

We must then consider two basic processes which represent the main density heterogeneities in the mantle. The first is the behaviour of megaplumes and the other is the distribution of slabs. In general, the source variations of the moment of inertia are generated by the two components, the moment of density anomalies and the moment of dynamic topographies induced by these anomalies. The resulting moment of inertia, which consists of these two contributions and is usually much smaller than the magnitudes of the two individual contributions (because the two have opposite signs), can have the same sign, or even an opposite sign, as the moment of inertia due to the density anomalies by themselves. This result would depend on the internal constitution of Earth, i.e. its rheological stratification and the exact nature of the seismic discontinuities. The present-day distribution of subduction locations, which lie on small circles with respect to Pavoni's geotectonic network, as well as the two megaplumes determining the axis of this network, induce the same basic effect. The density anomalies by themselves, without the dynamically induced topographies, attempt to shift the rotational axis towards Pavoni's axis. There is, however, the opposite contribution from dynamic topographies. We can deduce from the present-day position of the rotational axis that the effect of topographies is stronger because the induced topographies try to orient the rotational axis perpendicular to the geotectonic axis.

There are three possibilities for keeping the principal axis of the total moment of inertia (PATMI) due to all sources located perpendicular to the geotectonic axis:

(1) The PATMI due to the megaplumes is near the z-axis but the PATMI due to the slabs is close to the geotectonic axis and the influence of the megaplumes is stronger.
(2) The PATMI due to the slabs is near the z-axis but the PATMI due to the megaplumes lies near the geotectonic axis and the influence of the slabs is stronger.
(3) Both PATMIs are near the z axis.

We cannot decide which possibility is most likely without conducting direct modelling and obtaining more detailed knowledge of Earth's interior, and particularly its physical properties. Nevertheless, there is another source of valuable information, and that is the relative stability of Earth's rotational axis in the hotspot reference frame over the past few tens of millions of years [51]. This fact places an important constraint on the ability of Earth's pole to wander freely and suggests rather that it is controlled, more or less, by megaplumes acting as strong attractors in the lower mantle. The characteristics of the strong attractor have already been revealed by 2D [33,35] and 3D [34] models. These models invariably show that the downwellings are strongly time dependent. On the other hand, we see that PATMI due to megaplumes may be stable and, therefore, may exert tremendous influence on the stability of the actual position of the rotational axis. Of course, there is the possibility of catastrophic flushing events, which might excite the rotational axis episodically [37–41].

A similar mechanism was proposed by Bills and Fischer [52] for Venus, where there are four major features evident in the gravity and topography: the Atla, Beta, Ovda and Thetis regions. Three of these regions (Atla, Ovda and Thetis) lie very close to the equator and may be interpreted as surface expressions of upwelling mantle plumes that have dynamically determined the equator as they have formed.

5. Concluding remarks

In this work we hav proposed a possible physical explanation for the existence of megaplumes in the mantle. Our arguments are based on the potential importance of radiative transfer, a long neglected subject among geodynamicists. Our calculations show the importance of radiative transfer in several aspects, which are worth reiterating. First, the development and stability of the megaplumes is revealed. Second, the creation of the very hot blobs, which can now be tolerated by the high melting curve for perovskite measured recently [30], and the formation of very cold blobs into a hot lower mantle, are consequences of the large asymmetry between the hot and cold flows in the presence of the radiative transfer operating primarily in the deep mantle. These results were obtained for a cartesian geometry and without the presence of other depth-dependent properties, such as thermal expansivity and viscosity. These additional attributes would further aggravate the vertical asymmetry and will strengthen the position of the attractor in the lower mantle. All things considered, the existence of the megaplumes as detected from seismic tomography does have a physical explanation, which relies on both the depth-dependent and the temperature-dependent properties of the lower mantle material. Further studies in 3D spherical geometry will shed greater light on the dynamics of these large upwellings, which, in a way, serve as the beacon through the murky tranquility of the lower mantle.

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