Seismic hemispheric asymmetry induced by Earth's inner core decentering

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In a first approximation the Earth's interior has an isotropic structure with a spherical symmetry. Over the last decades the geophysical observations have revealed, at different spatial scales, the existence of several perturbations from this basic structure. Some of them are situated in the neighborhood of the inner core boundary (ICB). One of the best documented perturbations is the asymmetry at the top of the inner core (ATIC) characterized by faster seismic wave velocity in the eastern hemisphere than in the western hemisphere. All existing explanations are based on a hemispheric variation of the material properties near ICB inside the inner core. Using numerical simulations of the seismic ray propagation, we show that the ATIC can be explained as well by the displacement of the inner core towards east in the equatorial plane tens of kilometers from the Earth's center, without modifying the spherical symmetry in the upper inner core. The hypothesis of a displaced inner core is also sustained by other observed hemispheric asymmetries at the top of the inner core and at the bottom of the outer core. A displaced inner core would have major implications for many mechanical, thermal, and magnetic phenomena in the Earth's interior.

I. INTRODUCTION

Over the last decades the geophysical observations have revealed the existence of several perturbations of the Earth's interior from an isotropic structure with a spherical symmetry [1–16]. One of the best documented perturbations is the asymmetry at the top of the inner core (ATIC) characterized by faster seismic wave velocity in the eastern hemisphere than in the western hemisphere [3–6, 8, 9, 16]. All existing explanations assume a hemispheric variation of the material properties near the inner core boundary (ICB) inside the inner core [5, 6, 8, 9, 16, 17]. We show that the ATIC can be explained as well by the displacement of the inner core towards east in the equatorial plane tens of kilometers from the Earth's center, without modifying the spherical symmetry in the upper inner core.

The Earth's inner core is a rigid sphere surrounded by the fluid with smaller density of the outer core. Therefore, in the mechanical equilibrium with respect to the gravitational and hydrostatic forces, its center of mass coincides with the Earth's center. The displacements from the equilibrium position have been attributed to harmonic oscillations with amplitudes of at most 0.5 m and periods of 4-8 hr [18, 19]. Movements over tens of kilometers would imply the presence of some forces balancing the gravitational one. They could originate from the interaction of the inner core with the flow in the outer core and with the terrestrial magnetic field [11, 20, 21]. The angular momentum conservation would cause a global scale flow in the outer core, influencing the generation of the geomagnetic field. Therefore, the time scale of the large amplitude movements of the inner core may coincide with that of the variations of the magnetic field, being larger than thousands of years [11, 21, 22]. The angular momentum conservation would also imply changes in angular velocity and rotation axis of the inner core, as several seismic studies suggest [11, 23, 24]. In this letter we leave aside the dynamical aspects of the inner core movement and focus on an imaging interpretation of the seismic data in order to obtain information on the actual position of the inner core.

II. SEISMIC RAYS FOR DECENTERED INNER CORE

ATIC manifests itself predominantly in the residuals of the differential travel time of the PKIKP and PKiKP seismic phases [5, 6, 8, 9, 16]. They both travel through almost the same regions of the crust, mantle, and outer core. After that, the PKiKP phase reflects off the ICB, while the PKIKP phase refracts twice on ICB propagating inside the inner core. If the inner core is displaced from the Earth's center, then the paths of the two seismic phases change after reflection and refraction on its boundary (Fig. 1a). We denote by $\mathrm{PKIKP_{dec}}$ and $\mathrm{PKiKP_{dec}}$ the paths modified by the decentered inner core. Unlike the paths for the centered inner core, their propagation plane changes at reflection or refraction on ICB.

We compute the differential travel time Δt by subtracting the travel time of the PKIKP phase from the travel time of the PKiKP phase with the same epicentral distance. We denote by Δt_0 the differential travel time computed from the velocity profile of a 1D reference seismic model. The observational data show that the residuals $\Delta t - \Delta t_0$ are positive in the eastern hemisphere and negative in the western hemisphere [5, 6, 8, 9, 16]. Un-

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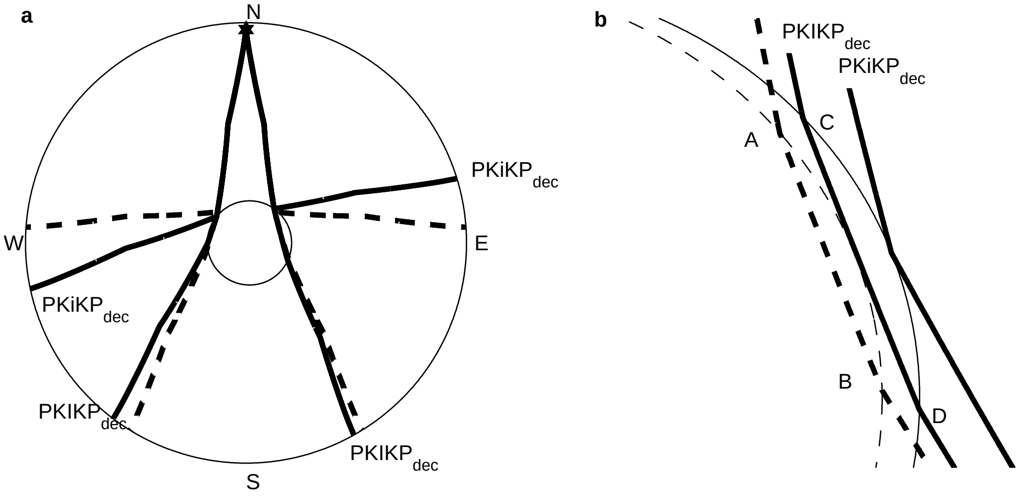

FIG. 1. Propagation of the PKIKP seismic phase for decentered inner core. (a) The paths of the PKIKP$_{\rm dec}$ and PKiKP$_{\rm dec}$ rays (thick continuous lines) when the inner core (the small circle) is displaced from the Earth's center with 100 km towards east. The propagation plane of the seismic ray contains the centers of both Earth and decentered inner core and in this case it is not modified by refraction on ICB. The dashed lines represent the paths of the same phases for the centered inner core. All the represented seismic rays have the same initial incidence angle; hence they are identical until the incidence with the ICB. After that, the paths for the centered inner core are symmetric, while PKIKP$_{\rm dec}$ and PKiKP$_{\rm dec}$ rays clearly exhibit an east-west asymmetry. (b) The path inside the eastern hemisphere of the decentered inner core of the PKIKP$_{\rm dec}$ ray presented in panel a. The PKIKP (thick dashed line) and PKiKP$_{\rm dec}$ rays have not the same initial incidence angle as in panel a, but they emerge at the same point on the Earth's surface as the PKIKP$_{\rm dec}$ ray. The circular arcs are the ICB when the inner core is decentered (continuous line) and when it is centered (dashed line).

der the hypothesis that the inner core is concentric with the Earth, this asymmetry is explained by the greater (smaller) seismic wave velocity at the top of the inner core in the eastern (western) hemisphere than the velocity of the 1D reference models.

When the inner core is decentered, the epicentral distance and the travel time of the PKIKP$_{\rm dec}$ and PKiKP$_{\rm dec}$ phases depend on the initial propagation plane of the seismic ray and on the earthquake focus location. Because of the shifted position of the inner core, the total length, from focus to exit point, of the PKIKP$_{\rm dec}$ ray is smaller than that of PKIKP corresponding to the centered inner core (Fig. 1b). The length of the reflected ray PKiKP$_{\rm dec}$ also decreases by approximately the same amount. In the diametrically opposite region of the inner core both lengths have approximately the same increase. These changes in path lengths for the pairs of reflected and refracted phases do not change the differential travel time $\Delta t_{\rm dec}$.

There is another geometric effect which modifies the differential travel time $\Delta t_{\rm dec}$. The segment CD of the seismic ray within the decentered inner core is longer than the segment AB for the centered inner core (Fig. 1b). Because the velocity in the inner core is larger than in the outer core, the travel time of the PKIKP$_{\rm dec}$ phase has an additional decrease, the differential travel time $\Delta t_{\rm dec}$ increases, and the residual $\Delta t_{\rm dec} - \Delta t_0$ is positive. In the diametrically opposite region of the inner core the distance CD is smaller than AB and the residual is negative, resulting in a hemispheric asymmetry. Hence, the asymmetry of the residuals of the differential travel time can be explained by the variation of the PKIKP$_{\rm dec}$ ray paths in the decentered inner core without modifying the seismic velocities.

III. NUMERICAL RESULTS

The numerically computed residuals (Fig. 2) are quantitatively comparable with those observed [5, 6, 8, 9, 16] showing that displacements of the inner core over distances up to 100 km could explain ATIC. In the computations we assume that the velocity profile in the decentered inner core is that of the model ak135 [25]. Outside the inner core we also use the model ak135. It is linearly extrapolated to the points of the outer core situated at a smaller distance from the Earth's center than the inner core radius. Each of the two regions is divided into spherical layers with constant velocity of 1 km maximum thickness. The boundaries of the spherical layers also contain all the reference levels of the ak135 model. Therefore the numerical seismic rays consist of straight segments satisfying the refraction and reflection laws at the boundaries of the spherical layers. With the increase

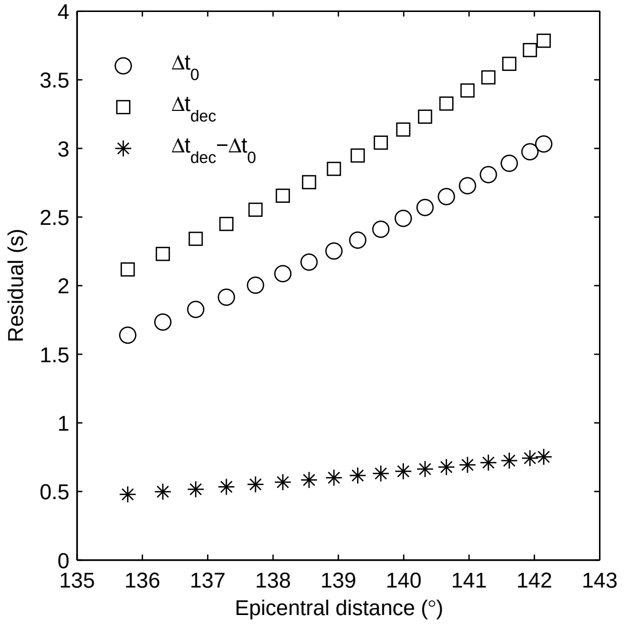

FIG. 2. Numerically computed residuals for a decentered inner core. The differential travel times $\Delta t_{\rm dec}$ are computed for the PKIKP$_{\rm dec}$ ray in the eastern hemisphere presented in Fig. 1b. We compute the reference differential travel time Δt_0 for the seismic model ak135 [25]. The variation range of the epicentral distance corresponds to the range 39-90 km of the turning point depth of the PKIKP ray in the centered inner core analyzed in [16].

of the turning point depth (epicentral distance) the positive residuals in the eastern hemisphere increase because the segment CD increases (see Fig. 1b).

In order to ascertain if a decentered inner core could explain ATIC, we should compare the longitudinal repartition of the residuals obtained by numerical simulations with those reported in [16], the most extensive and accurate PKiKP -PKIKP study to date. The positions of the simulated earthquake sources are given by the spherical coordinate angles with respect to the axis defined by the centers of the Earth and the decentered inner core. These angles vary by steps of 10°. The seismic rays are emitted from each focus in planes making with each other angles of 10°. We compute the residuals for the minimum depth below ICB (39 km) of the turning point of the PKIKP$_{\rm dec}$ ray for which observational data are available [16].

We computed the residuals for a displacement of the inner core of 100 km towards 90° east longitude (Fig. 3). If the displacement is in the equatorial plane, then the positive residuals are confined within the eastern hemisphere and the negative ones within the western hemisphere (Fig. 3a). The position of the boundary between the hemispheres with positive and negative residuals rotates with the angle between the plane of the 90° east meridian and the direction defined by the centers of the Earth and the decentered inner core. If the inner core is displaced outside the equatorial plane, the separation of the positive and negative residuals is not so definite (Fig. 3b).

In the observational data, the positive and negative residuals are sharply separated [16] corresponding to a displacement of the inner core in equatorial plane as in Fig. 3a. The boundary between them does not coincide with that between the eastern and western hemispheres, being shifted towards east by approximately 20°. All these indicate a displacement of the inner core with tens of kilometers in equatorial plane towards 110° east longitude.

In comparing the results of the numerical simulations with the observational data we have to take into account the simplifying hypotheses of the numerical simulation as well as the observational errors. For instance, we use the velocities of the ak135 model obtained under the hypothesis that the inner core is centered. Or the observational differential travel times PKiKP-PKIKP have fluctuations around the values derived from the model ak135 with an amplitude of 0.5 s [25], comparable with the values associated with ATIC [16]. That is why the exact longitude separating the positive and negative observed residuals and its variation with the turning point depth of the seismic rays cannot be determined precisely. The observational data suggest an eastward shift of the hemisphere boundary with increasing depth, while the numerical simulation shows that it does not vary with the depth.

IV. DISCUSSION AND CONCLUSION

There are other seismic phenomena with east-west asymmetry explained by a decentered inner core, but none of them has a complete observational description of the longitudinal variation. For instance, ATIC is associated to a hemispheric asymmetry of the seismic waves attenuation [6, 9, 10, 26–29] which seems to be confined to the uppermost inner core [10, 26]. Existing explanations of the attenuation asymmetry require a trade-off between attenuation and velocity structures in the inner core and velocity structure at the bottom of outer core [6, 9]. If the inner core is decentered, the PKIKP$_{\rm dec}$ phase propagates in the eastern hemisphere over a longer distance inside the inner core (segment CD in Fig. 1b) than in the western hemisphere. Since the quality factor Q is two orders of magnitude larger in the outer core than in the inner core [25], the attenuation Q^{-1} in the eastern hemisphere is larger than in the western hemisphere.

Another example of hemispheric asymmetry is the observation that PKiKP phases sampling the eastern hemisphere arrive by about 0.9 s earlier than those sampling the western hemisphere [8]. When the inner core is displaced eastwards, the length of the PKiKP$_{\rm dec}$ ray in the eastern hemisphere is smaller than in the western hemisphere (Fig. 1b). Our numerical simulations reproduce fairly well the observed PKiKP travel time hemispheric

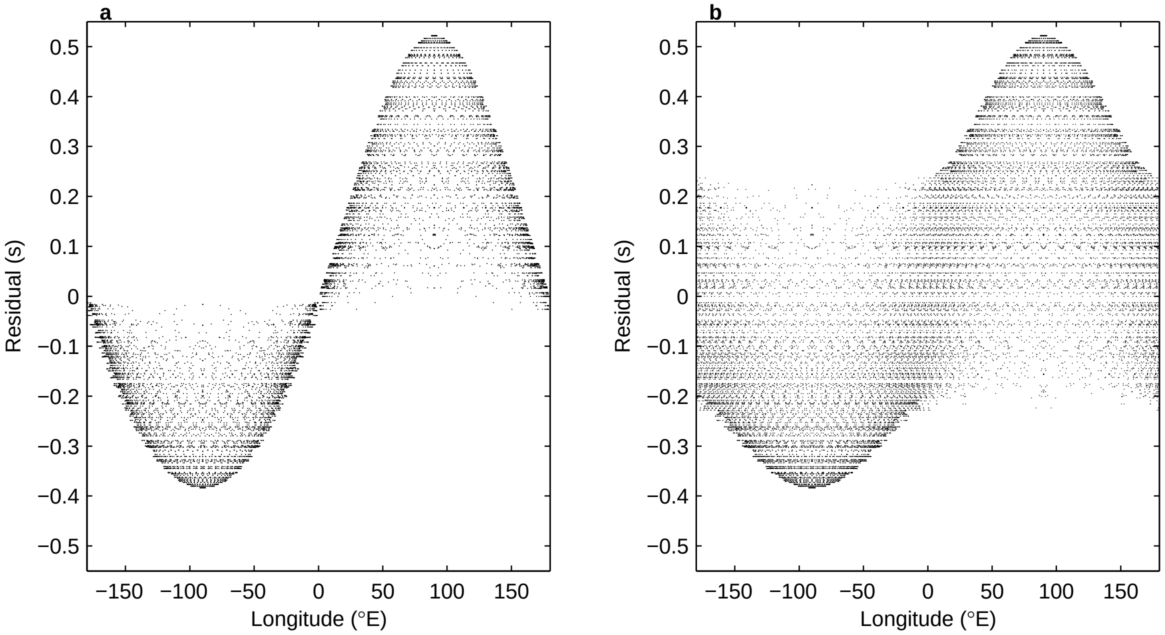

FIG. 3. Longitudinal distribution of the residuals obtained by numerical simulation. The inner core is displaced with 100 km towards 90° east longitude in the equatorial plane (a) and along a direction making an angle of 30° with the equatorial plane (b). On the abscissa we have the longitude of the turning point of the PKIKP ray refracted by a centered inner core which emerges at the same point on the Earth's surface as the $\text{PKIKP}_{\text{dec}}$ ray refracted by a decentered inner core.

asymmetry.

The displacement of 100 km of the inner core should produce noticeable effects in the neighborhood of the ICB at the bottom of the outer core as well. If r_c is the radius of the inner core, then the distances from the Earth's center to the ICB would vary between $r_c - 100$ and $r_c + 100$. If the inner core were decentered but the seismic model assumes that it is centered, the interpretation of the seismic observations would have larger errors in the spherical layer of 200 km containing the ICB than in other regions of the Earth's interior. Indeed, the reference 1D seismic models are different from each other over a thickness of roughly 200 km above ICB [8–10].

A decentered inner core should cause hemispheric asymmetries in the repartition of the physical quantities above ICB. Therefore our numerical model is only a first order approximation and other consequences of the inner core displacement on the structure of the Earth's interior have to be analyzed.

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