Regional Variation of Inner Core Anisotropy from Seismic Normal Mode Observations

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Earth’s solid inner core is surrounded by a convecting liquid outer core, creating the geodynamo driving the planet’s magnetic field. Seismic studies using compressional body waves suggest hemispherical variation in the anisotropic structure of the inner core, but are poorly constrained because of limited earthquake and receiver distribution. Here, using normal mode splitting function measurements from large earthquakes, based on extended cross-coupling theory, we observe both regional variations and eastern versus western hemispherical anisotropy in the inner core. The similarity of this pattern with Earth’s magnetic field suggests freezing-in of crystal alignment during solidification or texturing by Maxwell stress as origins of the anisotropy. These observations limit the amount of inner core super rotation, but would be consistent with oscillation.

As the Earth continues to cool, the inner core grows by solidification of the fluid outer core (1). Solidification results in the release of light elements and latent heat, which drive the geodynamo generating the Earth’s magnetic field (2). The details of the magnetic field and geodynamo depend on the existence and structure of the inner core, which can be studied directly by using seismic data. Seismological observations established that the inner core is anisotropic (3,4) and possibly rotating faster than the Earth’s mantle (5).

Recent seismic studies have suggested the existence of hemispherical variations in anisotropy—the Western Hemisphere displaying much stronger anisotropy than the Eastern Hemisphere (6), which may be related to the thermal evolution of the core-mantle boundary region and the structure of the magnetic field (7). However, hemispherical variations in inner core anisotropy have so far been seen only in compressional body waves (6,8), which are limited to sampling only a few small regions of the core because of uneven station and earthquake coverage. These potential biases limit their use in making comparisons of inner core structure with the Earth’s magnetic field and thermal structure. Hemispherical variations may be too simplistic an interpretation of more complicated laterally varying structure, and we do not know if they also exist in shear waves.

Normal modes—whole Earth oscillations at the lower part of the frequency range (<10 mHz)—have the potential to provide both full global coverage and robust identification of hemispherical variation in inner core anisotropy. However, lack of appropriate theory has prevented the resolution of more complicated structures and regional variations by using this approach. The simplest theory to study normal modes, called self-coupling, assumes that a mode may be treated as isolated (9). All previous normal mode studies have applied self-coupling and have sought only inner core anisotropy that is symmetric around the Earth’s rotational axis (4,10–12). To observe hemispherical (i.e., antisymmetric) variations, it is essential to take cross-coupling between pairs of modes into account (13). Cross-coupling becomes important when two or more normal modes are close in the frequency spectrum and start to resonate (14). We recently extended normal mode theory (15), enabling us to include hemispherical variations in inner core anisotropy, and apply it here to make observations in real data (16). Here, we present normal mode splitting function measurements from normal mode spectra from over 90 large earthquakes (moment magnitude > 7.5) from 1976 to 2009 to observe hemispherical anisotropy and to interpret these observations using model predictions (17). Spherical normal modes are denoted \( S_n l \), where \( n \) is the overtone number and \( l \) is the angular order. \( J \) denotes modes that are confined to the inner core (fig. S1 and S2).

Normal mode \( 16S_5 \) strongly cross-couples to inner core confined mode \( 15S_4^2 \). The self-coupling splitting function measurement for \( 16S_5 \) (Fig. 1A) confirms earlier measurements (12,18) in which a symmetric zonal pattern (i.e., constant with longitude), with alternating bands across the polar regions and along the equator, is apparent. This characteristic pattern requires cylindrical inner core anisotropy (12) in addition to heterogeneous mantle structure (Fig. 1B) because calculations for mantle-only structure do not explain the anomalous polar regions. Instead, weaker subduction zone anomalies would be visible beneath the Americas and east Asia (Fig. 1C).

The observed cross-coupled splitting function between \( 16S_5 \) and inner core confined mode \( 15S_4^2 \) shows an antisymmetric flip in sign across Africa (Fig. 1D). Calculations, with the use of our previously developed theory (15), for a model with inner core anisotropy in the Western Hemisphere only (fig. S3) show that this flip can be explained by strong hemispherical variation in inner core anisotropy. The negative splitting function anomalies around the polar regions in the Western Hemisphere are due to increased anisotropy there, and the positive splitting function anomalies in the Eastern Hemisphere pole regions are due to locally weaker anisotropy (Fig. 1E). The pattern completely disappears when stripping the hemispherical inner core anisotropy from the predictions, leaving a mantle-only structure (Fig. 1F), confirming that this mode pair is very sensitive to inner core structure.

A range of tests (19), including cross-validation to determine error boundaries in our measurements (fig. S5), show that our observations are robust. Conveniently, the strongest cross-coupling for inner core hemispherical structure is found in normal mode pairs of which one of the modes is an oscillation of the inner core only, a so-called inner core confined mode. An inner core confined mode is not sensitive to the outer core, mantle, or crust (fig. S2) and can cross-couple with another mode only in the presence of inner core structure. Previous studies suggested that normal mode observations of inner core anisotropy may be due to outer core structure instead (20) or that the hemispherical variations seen in compressional waves may be due to anomalous structure in the core-mantle boundary region. By making use of pairs that are sensitive only to hemispherical inner core structure, we show that any observed structure must instead come from the inner core, which provides evidence for the existence of inner core anisotropy. It is also noteworthy that the normal modes observed here are mainly sensitive to the shear wave structure of the inner core; this suggests that regional variations in anisotropy can be observed not only in compressional but also in shear wave velocity.

Several more pairs of cross-coupled modes show the characteristic antisymmetric change in signature across Africa in their cross-coupled splitting functions (fig. S2). Mode pair \( 9S_5^2S_5^{10} \) (Fig. 2A) is again a combination of an inner core confined mode with an observable mode. Comparison with model predictions (fig. S4A) shows that the alternating pattern with negative splitting function anomalies near the poles in the Western Hemisphere is due to increased anisotropy and that the anomalies with opposite polarity in the Eastern Hemisphere are due to weaker anisotropy; the observed and predicted patterns are similar. Both constituent modes of the pair \( 14S_2^{11}S_5^8 \) (Fig. 2B) are observable at the Earth’s surface, and both are sensitive to mantle and core structure. The cross-coupled splitting function for \( 14S_2^{11}S_5^8 \) is a combination of mantle and core structure, showing much stronger antisymmetric splitting than is predicted for current models of inner core anisotropy (fig. S4B). For this mode pair, the predictions confirm that increased
anisotropy in the Western Hemisphere shows up as positive splitting function anomalies in the polar regions.

Short-period differential PKPbc-PKIKP and PKPab-PKIKP travel times allow for comparison of splitting functions with body wave observations, revealing inner core structure by using pairs of waves that have similar paths in the mantle and outer core but differ in the inner core (fig. S6). PKIKP is the compressional wave propagating from the mantle into the outer and inner core and returning to the Earth’s surface. PKPbc and PKPab are branches of compressional waves that travel only the mantle and outer core. In agreement with previous studies (6), polar paths show large, positive travel-time anomalies in the Western Hemisphere and smaller anomalies in the eastern hemisphere (Fig. 3). These anomalies support the general interpretation that inner core anisotropy is aligned with the north-south axis in the Western Hemisphere and is weaker in the Eastern Hemisphere. The boundaries between the Eastern and Western Hemispheres at 14°E and 151°W, revealed using a model space search, serve as boundaries for the cross-coupled hemispherical inner core anisotropy predictions (Fig. 1E and fig. S4).

The strongest anisotropy in the PKIKP observations is found in the Western Hemisphere under the Americas. These observations are dominated by earthquakes in the South Sandwich Islands and stations in Alaska; sampling of other regions by polar paths is much sparser. This
region very closely matches the area of strongest anisotropy found independently in our observations of cross-coupled, normal mode splitting function (Figs. 1D and 2). The normal modes also reveal that the region of weakest anisotropy lies under eastern Asia, an area that is not well covered by PKIKP paths.

Inspecting the observed splitting functions in more detail, we find a pattern of regional variations in addition to the simple Eastern versus Western Hemisphere division in the PKIKP observations. The splitting function predictions for simple hemispheres are antisymmetric across Africa (Fig. 1E and fig. S4), whereas the observations show wide transition zone regions between the narrow regions of strongest and weakest anisotropy. The observations also show regions of variable strength on either side of the hemisphere boundary across Africa (21). For example, \( S_3 - S_1 \) (Fig. 2A) reveals an additional negative frequency region under southern Africa and in the mid-Pacific. Similar additional features are seen in \( S_3 - S_2 \) (Fig. 1D) beneath Madagascar.

Inner core anisotropy is acquired either during solidification by freezing-in of crystal alignment (7, 22), or by deformation texturing after solidification due to thermal convection (23) or anisotropic growth (24). Magnetic flux patches are caused by variations in temperature at the core-mantle boundary, locally extracting more or less heat from the core and thus concentrating upwellings and downwellings in outer core convection (30). Complex convection patterns may then imprint variable alignment during freezing at the inner core boundary (7). The question remains whether the flux patches have been stable for long enough in Earth’s history to generate hemispherical differences in the deeper parts of the inner core, but the deeper anisotropy may have been acquired after solidification due to texturing by Maxwell stress (25, 26). Thus, hemispherical variations in seismic anisotropy may help in unraveling the magnetic field of the past.

Inner core super rotation of 0.1° per year (5) would average out hemispherical variations caused by texturing either during or after solidification. We find that the areas of weak and strong anisotropy do not cover a full hemisphere but are narrow and separated by wide transition regions. This might also be explained by inner core oscillation, which would make the boundary between the two hemispheres blurred.

References and Notes
13. Self-coupling is sensitive only to even-degree structure for symmetry reasons. Hemispheres are an odd-degree structure, which requires cross-coupling.
17. Materials and methods are available as supporting material on Science Online.
19. Adding hemispherical structure improved the data misfit (table S1), proving that such structures are required by the data. We also find that the flip in sign is independent of the starting model used in the inversion and appeared without an a priori imposed boundary there.
32. J. Ritsema and H. van Heijst assisted in building the model.
33. The similarity between the locations of regional flux concentrations in the radial magnetic field and the strength of the seismic anisotropy suggests that they share a common origin and rules out deformation by thermal convection (23) or anisotropic growth (24). Magnetic flux patches are caused by variations in temperature at the core-mantle boundary, locally extracting more or less heat from the core and thus concentrating upwellings and downwellings in outer core convection (30). Complex convection patterns may then imprint variable alignment during freezing at the inner core boundary (7).
34. The two flux patches in the Eastern Hemisphere are stronger and are associated with the weakest anisotropy in the same hemisphere. Weak magnetic field regions are seen across Africa and in the Pacific, in agreement with the transition regions between strong and weak anisotropy in normal mode observations.
35. For example, \( S_3 - S_1 \) (Fig. 2A) reveals an additional negative frequency region under southern Africa and in the mid-Pacific. Similar additional features are seen in \( S_3 - S_2 \) (Fig. 1D) beneath Madagascar.
36. We further constrain the areas of strongest anisotropy across the Americas and weakest anisotropy across eastern Asia (comparing Fig. 1D with Fig. 4B). For example, \( S_3 - S_1 \) (Fig. 2A) reveals an additional negative frequency region under southern Africa and in the mid-Pacific. Similar additional features are seen in \( S_3 - S_2 \) (Fig. 1D) beneath Madagascar.
37. We estimate that the areas of strongest anisotropy across the Americas and weakest anisotropy across eastern Asia (comparing Fig. 1D with Fig. 4B). We estimate that the areas of strongest anisotropy across the Americas and weakest anisotropy across eastern Asia (comparing Fig. 1D with Fig. 4B). We estimate that the areas of strongest anisotropy across the Americas and weakest anisotropy across eastern Asia (comparing Fig. 1D with Fig. 4B).