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Mineral Physics Quest to the Earth's Core

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Because of its remoteness, together with pressures from 140 to 360 gigapascals and temperatures from 4000 to 7000 K, most direct observations of the Earth's core properties have come from teleseismic studies, requiring large earthquake sources and well-positioned seismometers to detect weak wave signals that have traversed the Earth's deepest interior. The decoding of geochemical signatures of the core—potentially carried to the surface in plumes originating at the core-mantle boundary—faces numerous challenges of the debated integrity of this hypothesis.

For these reasons, understanding the Earth's core requires multidisciplinary efforts. In the past two decades, deep-Earth scientists have unveiled a number of unusual and enigmatic phenomena of the core, including inner core anisotropy, differential rotation of the inner core, fine-scale seismic heterogeneity, and the possible existence of the prefer-oriented hexagonal close packed (hcp, in which two closely packed layers stack alternately along a crystallographic axis) and/or body-centered cubic (bcc, in which eight atoms reside at the corners and one atom resides at the center of the cubic cell) iron/nickel/light element alloys in the inner core (Figure 1). In this feature article, we summarize recent new findings and frontiers about the nature of the core from mineral physics research.

By L. Dubrovinsky and J.-F. Lin

Composition of the Core

Since the discovery of the core about a century ago, the concept of iron with 5–10% nickel being the dominant component of the core has been well established. In the 1950s, Harvard University geology professor Francis Birch first recognized that the outer core is less dense than iron or iron-nickel alloy at relevant pressures and temperatures of the core. Current estimates for the density deficit relative to iron, which requires the addition of a certain amount of element or elements lighter than iron, vary between 6 and 10% for the outer core and 2 and 5% for the inner core.

To be considered as a major light element in the core, the element must be abundant (at least a few percent by weight) and of low volatility or relatively siderophile ("iron loving") to be incorporated into the core during its formation. The elements should partition preferably to the liquid outer core and should have physical properties such as density and sound velocity that match seismic observations of the core. These constraints have resulted in oxygen and silicon as the likely candidates for being major light elements in the core; with sulfur accounting for part of the density deficit (but iron-sulfur alone having velocity-density relations uncharacteristic of the core [*Badro et al.*,

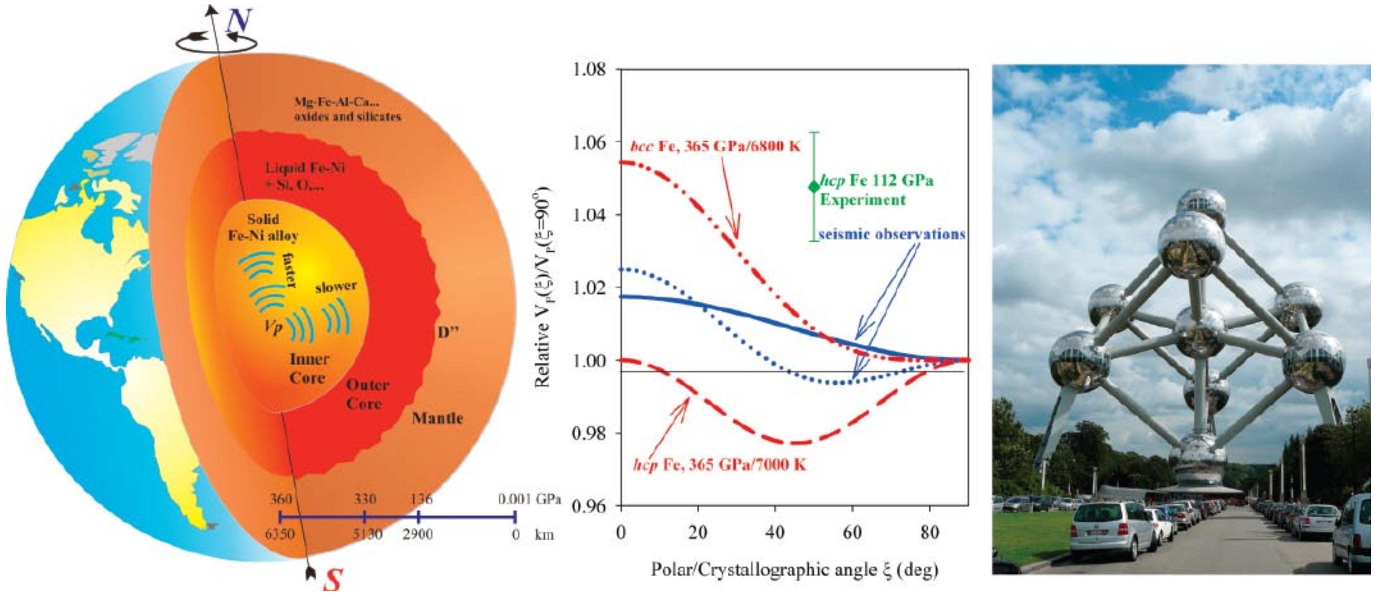

*Fig. 1. (left) An illustrated cutaway of the Earth's interior reveals seismic anisotropy of the inner core. (middle) Representative elastic anisotropies of single-crystal hexagonal close packed (hcp; red dashed line) and body-centered cubic (bcc; red dash-dotted line) iron from theory [*Belonoshko et al., 2008*], prefer-oriented hcp iron from static experiments at 112 gigapascals (green diamond) [*Antonangeli et al., 2004*], and seismic observations in the inner core (blue lines) are shown for comparison. Elastic anisotropy could be explained if the bcc iron-based alloy in the inner core had preferable orientation along Earth's rotation axis (similar to that of Atomium, right, a 102-meter-tall monument built for the 1958 World's Fair in Brussels, Belgium, which forms the shape of an iron crystal magnified 165 billion times) or a dominant amount of prefer-oriented hcp iron.*

2007]); and with carbon and hydrogen having major drawbacks due to their high volatility, which could have resulted in their loss during the formation of the planet. Current mineral physics results further indicate that a combination of silicon, oxygen, and possibly sulfur or carbon is needed to satisfy all of the aforementioned constraints simultaneously.

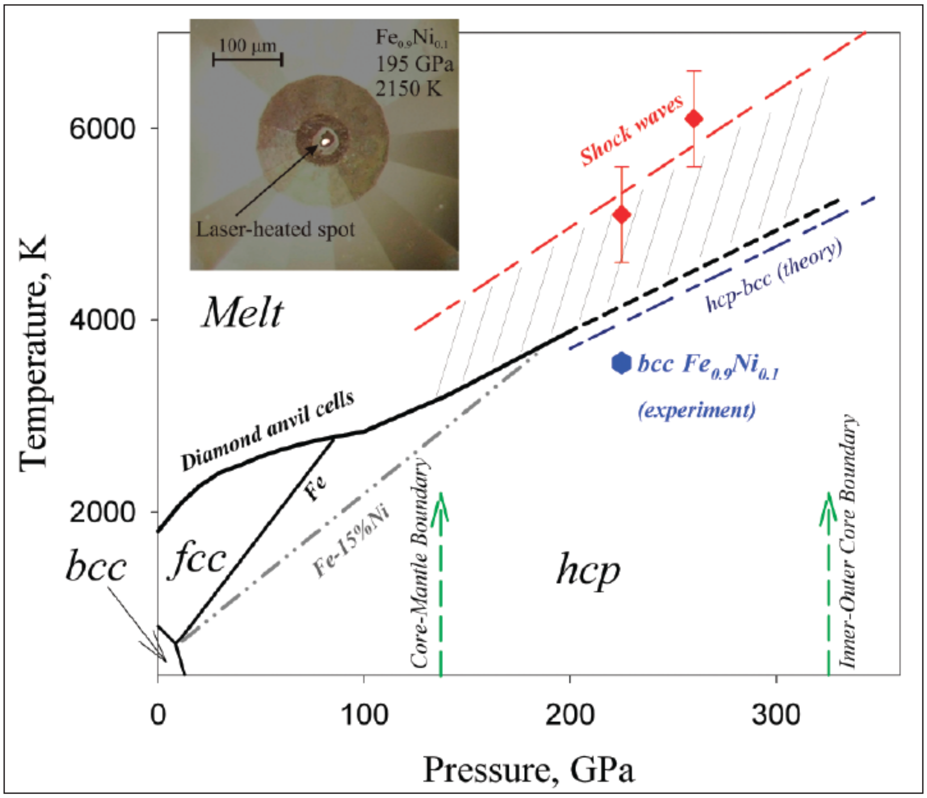

Fig. 2. Representative phase diagram of iron and iron-nickel alloys at high pressures and temperatures. The hcp iron is stable over a wide range of pressures and temperatures, while bcc iron is predicted to exist in the inner core (blue dashed line) and bcc iron with 10% nickel alloy is experimentally observed at 225 gigapascals and 3400 K (blue hexagon). Melting curves of iron measured from shock waves (red diamonds) are much higher than static diamond cell results (black dashed line). Shaded area indicates current survey of the melting temperatures of iron at core pressures; inset shows hcp iron with 10% nickel alloy at 195 gigapascals and 2150 K.

Structure of Iron and Its Alloys

Iron crystallizes in the bcc structure under ambient conditions. In the 1960s, high-pressure X-ray diffraction revealed the existence of hcp iron at pressures above approximately 10 gigapascals (Figure 2). Since then, hcp iron has been found to be stable over a wide range of pressures and temperatures approaching the suspected core conditions. The layered structure of iron can result in various stacking polymorphs such as the face-centered cubic (fcc) phase, in which the three most closely packed layers stack alternately along a crystallographic direction at above 1200 K and room pressure. While hcp iron is the "holy grail" of the core, considerable research attention has been paid to the behavior of iron/nickel/light element alloys at high pressures and temperatures. In particular, the addition of nickel to iron has been found to stabilize the fcc phase with respect to the hcp phase to higher pressures. The extrapolation of the hcp-fcc phase boundary, nevertheless, indicates that iron with 10–15% nickel at inner core conditions (pressure above 330 gigapascals and temperature above approximately 4500 K) is likely stable in the hcp structure.

A phase transition of solid hcp iron at core conditions was first proposed using dynamic shock wave results, whereas recent theoretical calculations suggest that hcp iron transforms into bcc iron at conditions close to the melting point of iron at core pressures (Figure 2) [*Vočadlo et al.*, 2003; *Belonoshko et al.*, 2008]. To the surprise of mineral physicists, as they generally expect to find the densest structures at the crushing pressures of the core, bcc iron with 10% nickel alloy (which is not the densest structure) was recently observed at above 225 gigapascals and 3400 K [*Dubrovinsky et al.*, 2007]. The addition of a light element such as silicon to iron appears to stabilize the bcc iron alloy to much higher pressures and temperatures. These surprising observations on the existence of bcc iron alloys indicate that the inner core could be a mixture of hcp and bcc iron alloys, instead of the hcp phase alone.

Sound Velocities and Seismic Anisotropy

One of the most fascinating seismic observations lies in the inner core anisotropy: Seismic waves travel 3–4% faster along the polar axis of the Earth's core than in the equatorial direction. While a number of hypotheses have been proposed to explain the anisotropy, the general consensus is that the anisotropy is due to the preferred orientation of the iron crystals. Indeed, hcp iron displays strong lattice-preferred orientation with its crystallographic c axis parallel to the compression axis of the high-pressure diamond anvil cell as a result of plastic basal slip. Furthermore, experimental measurements and ab initio finite temperature molecular dynamics simulations show that the maximum difference in compressional wave velocity of hcp iron is 4–6% at megabar pressures [*Antonangeli et al.*, 2004; *Vočadlo*, 2007]. However, the simulation of sound wave propagation in the material by means of the molecular dynamics [*Belonoshko et al.*, 2008] showed that elastic anisotropy of hcp iron rapidly decreases with increasing temperature at inner core pressures.

To account for the overall 3–4% seismic anisotropy in the inner core, a predominant amount of the hcp iron has to be preferentially aligned, suggesting the existence of a gigantic iron crystal in the inner core. Because single-crystal bcc iron exhibits up to 12% anisotropy in the compressional wave velocity in theoretical simulations under inner core conditions [*Belonoshko et al.*, 2008], the predicted anisotropy of bcc iron would be sufficient to explain the seismic anisotropy of the inner core. The predicted transition from hcp to bcc iron may explain the variation in seismic anisotropy from the uppermost layer toward the inner layer of the inner core.

Because laboratory-measured sound velocities of iron alloys generally follow a linear compressional velocity-density relation, traditionally called Birch's law, linear extrapolation and interpolation using sound velocity/density lines of candidate iron alloys are commonly used to estimate the amount of light elements in the core without considering high-temperature effect. Theoretical calculations suggest that Birch's law is probably valid even at high temperature [*Vočadlo*, 2007]. It is experimentally found, however, that high temperature can affect the velocity-density line of hcp iron at high pressures, indicating that high-pressure/high-temperature results are needed to reliably interpret seismic observations [*Lin et al.*, 2005].

Thermal Structure

One of the major uncertainties in modern geophysics is the temperature profile of the core, information fundamental for understanding the heat budget, thermal history, and geodynamics of the Earth's interior. The solidification of iron alloys at the inner core/outer core boundary provides a crucial anchor point because the melting curve of the core-forming alloy at 330 gigapascals would provide an upper bound and a lower bound of the temperature for the inner core and outer core, respectively. Following the adiabatic temperature distribution of the outer core as rationalized from its thermal conduction and convection behavior, the temperature at the top of the outer core and the thermal gradient across the core-mantle boundary can then be evaluated together with the lower-mantle temperature profile.

At the conditions of the inner and outer core, the only experiments possible at the moment are by dynamic shock wave techniques. Step by step, static diamond-cell experiments have reached to more than 200 gigapascals and high temperatures, but the detection of melting onset at such extreme conditions remains highly debated. The extrapolation of these results gives 5000–7000 K on the melting of iron at 330 gigapascals (Figure 2), with different theoretical calculations supporting different experimental estimates. Such a discrepancy of approximately 2000 K translates into drastic uncertainty in evaluating the thermal history and heat budget of the core and the core-mantle boundary. The melting temperature depression and subsolidus phase relations in iron/nickel/light element alloys at the Earth's core conditions add further uncertainties in estimating its thermal structure.

Future Missions

The mineral physics quest to the Earth's core falls largely on stably creating and simultaneously measuring pressure-temperature conditions of the subjected candidate iron alloys. Though measuring physical properties at the core conditions remains extremely difficult, as the typical sample size is only of the order of a few tens of micrometers, ongoing collaborative efforts by mineral physicists in the past decade have made it possible to directly probe some of these properties in situ statically using advanced synchrotron light sources and detecting techniques. Scientists are also gearing up in building new facilities that will help couple dynamic shock wave techniques with synchrotron light sources so as to allow in situ probing of these properties under extreme dynamic conditions. Efforts to search for and develop universal pressure and temperature scales are also under way to establish consistent results for a coherent picture of the core. The expectation of mineral physicists involved with these efforts is that within a decade, these mineral physics missions to the Earth's core will provide crucial information to greatly enhance our understanding of the nature of the core.

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Author Information

Leonid Dubrovinsky, University of Bayreuth, Bayreuth, Germany; E-mail: Leonid.Dubrovinsky@uni-bayreuth.de; and Jung-Fu Lin, University of Texas at Austin

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Examining the Scientific Consensus on Climate Change

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Fifty-two percent of Americans think most climate scientists agree that the Earth has been warming in recent years, and 47% think climate scientists agree (i.e., that there is a scientific consensus) that human activities are a major cause of that warming, according to recent polling (see http://www.pollingreport.com/enviro.htm). However, attempts to quantify the scientific consensus on anthropogenic warming have met with criticism. For instance, *Oreskes* [2004] reviewed 928 abstracts from peer-reviewed research papers and found that more than 75% either explicitly or implicitly accepted the consensus view that Earth's climate is being affected by human activities. Yet Oreskes's approach has been criticized for overstating the level of consensus acceptance within the examined abstracts [*Peiser*, 2005] and for not capturing the full diversity of scientific opinion [*Pielke*, 2005]. A review of previous attempts at quantifying the consensus and criticisms is provided by *Kendall Zimmerman* [2008]. The objective of our study presented here is to assess the scientific consensus on climate change through an unbiased survey of a large and broad group of Earth scientists.

An invitation to participate in the survey was sent to 10,257 Earth scientists. The database was built from *Keane and Martinez* [2007], which lists all geosciences faculty at reporting academic institutions, along with researchers at state geologic surveys associated with local universities, and researchers at U.S. federal research facilities (e.g., U.S. Geological Survey, NASA, and NOAA (U.S. National Oceanic and Atmospheric Administration) facilities; U.S. Department of Energy national laboratories; and so forth). To maximize the response rate, the survey was designed to take less than 2 minutes to complete, and it was administered by a professional online survey site (http://www.questionpro.com) that allowed one-time participation by those who received the invitation.

This brief report addresses the two primary questions of the survey, which contained up to nine questions (the full study is given by *Kendall Zimmerman* [2008]):

1. When compared with pre-1800s levels, do you think that mean global temperatures have generally risen, fallen, or remained relatively constant?
2. Do you think human activity is a significant contributing factor in changing mean global temperatures?

With 3146 individuals completing the survey, the participant response rate for the survey was 30.7%. This is a typical response rate for Web-based surveys [*Cook et al.,* 2000; *Kaplowitz et al.,* 2004]. Of our survey participants, 90% were from U.S. institutions and 6% were from Canadian institutions; the remaining 4% were from institutions in 21 other nations. More than 90% of participants had Ph.D.s, and 7% had master's degrees. With survey participants asked to select a single category, the most common areas of expertise reported were geochemistry (15.5%), geophysics (12%), and oceanography (10.5%). General geology, hydrology/hydrogeology, and paleontology each accounted for 5–7% of the total respondents. Approximately 5% of the respondents were climate