PERSPECTIVES: EARTH'S INNER CORE

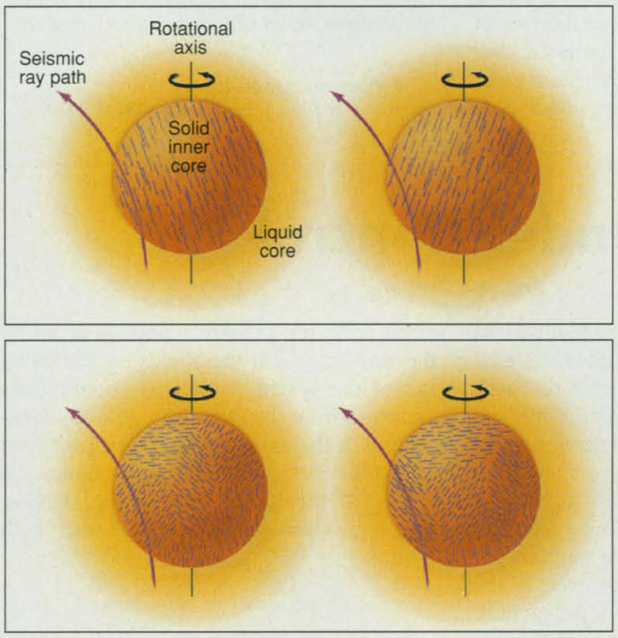
Is the Rotation Real?

Annie Souriau

The solid inner core of the Earth, a sphere of iron alloy with a radius of 1220 km (one-third the size of Earth's liquid core), has attracted the curiosity of a large community of scientists in various disciplines for at least a decade. One of the inner core's most remarkable properties is its anisotropy: Seismic waves propagate faster parallel to Earth's rotation axis than perpendicular to it. This 3 to 4% anisotropy in seismic velocities is probably due to the prevailing orientation of iron crystals that constitute the inner core, but the mechanism responsible for this orientation remains uncertain: Magnetic and dynamical processes have both been invoked.

Recently, three seismological studies (*1–3*) have suggested that the inner core rotates faster than the mantle, immediately provoking reactions from supporters and detractors alike. The search for this differential rotation was motivated by the predictions of some theoretical models of the dynamo that generates Earth's magnetic field inside the liquid core. However, the differential rotation rates inferred from seismology vary considerably among the studies, depending on the hypotheses and methods of detection. The problem is far from simple.

Song and Richards (*1*) and Su *et al.* (*2*) base their analyses on the assumption that the inner core exhibits a nearly cylindrical symmetry about an axis that is slightly tilted with respect to Earth's rotation axis (top part of figure). If the inner core does not rotate at the same speed as the mantle, it would then be possible to observe it from the apparent wobble of its symmetry axis. Song and Richards detected this wobble by studying seismic waves traveling from South Sandwich Island in the South Atlantic Ocean along a polar path to a seismometer in Alaska, whereas Su *et al.* considered the large, worldwide data set provided by the catalogs of the International Seismological Centre. The former found a rotation for the inner core that is 1.1°/year faster than that for the mantle over the 30 years of their observations, whereas the latter obtained a 3°/year faster rotation over the same interval. Yet both of these results raise some tough questions. In particular, the tilt of the symmetry axis is uncertain (*4*). It appears to be probably an artifact due to the uneven sampling of Earth by the seismic waves: Earthquakes occur mostly along subduction zones and mid-oceanic ridges, whereas stations are located mostly on continents. In addition, the uneven distribution of earthquakes in time may result in different axis positions when estimated over short time intervals. The anisotropy itself exhibits important departures from cylindrical symmetry or is superimposed on heterogeneities (*5*).



Inside story. Two approaches to detect the differential rotation of the inner core. (**Top**) The inner core anisotropy has a cylindrical symmetry, and its axis is tilted. When the inner core rotates (here half a turn), the orientation of the anisotropy with respect to an invariant seismic path varies, resulting in small variations in the propagation time (*1, 2*). (**Bottom**) The inner core exhibits anisotropy variations or heterogeneities. The rotation is detected from the transit of these heterogeneities beneath the seismic path, and the rotation rate may be estimated if a local anisotropy or heterogeneity pattern is available (*3*).

A more promising approach is to try to detect an inner core heterogeneity or anisotropy variation as it passes across a particular ray path, as attempted by Creager (*3*) (lower part of figure). Using South Sandwich Island events recorded at a network in Alaska, he first established a map of inner core anomalies in the region sampled by the rays and then used it to infer the inner core rotation rate from a specific path, where observations were available over a period of 30 years. He estimates values of 0.2° to 0.3°/year, but very low rates close to synchronous rotation are also possible, depending on how much of the signal is attributed to mantle heterogeneity.

Mantle heterogeneity may indeed introduce serious biases. For the path from South Sandwich Island to Alaska, the sources and receivers lie in the vicinity of subduction zones. Perturbing effects attributable to these structures are partly removed when the ray propagating through the inner core is compared with a nearby ray that stays inside the homogeneous liquid core, but residual effects still linger. It is thus hard to reach the extreme precision (0.3 s) required for detection. The effect of subduction zones is quite clear from the examination of the complete seismograms: For two events very close to each other, even phases unaffected by the inner core may exhibit substantial differences in travel times (*6*). Mislocating the earthquake hypocenter can also bias the travel times, in particular for the oldest events in the Southern Hemisphere, where the nearest station can be more than 2000 km away. For another polar path with simpler structures beneath source and station as well as accurate source locations—the Novaya Zemlya nuclear tests recorded in Antarctica—no travel time anomaly is observed over 25 years (*7*). Detecting such a subtle signal by seismology is likely to remain controversial.

Yet, the most serious problem with the differential rotation lies in its geodynamical consequences (*8*). Because Earth's mantle contains density heterogeneities, the resulting gravity field distorts the surface of the inner core, producing undulations on the order of 100 m in amplitude. This gravitational coupling is probably much larger than the magnetic coupling. If the inner core does not rotate at the same velocity as the mantle, its shape adjusts continually to the mantle-induced gravity field. This adjustment could occur by melting and solidification, because the iron at the inner core surface is close to its melting point. Or it could occur by viscous

The author is at the Observatoire Midi-Pyrénées, CNRS/UMR5562, 31400 Toulouse, France. E-mail: annie.souriau@cnes.fr

relaxation, if the inner core deforms easily. But in this case, one may question how the heterogeneities or anisotropy variations observed by seismologists could persist in the inner core.

Will seismology be able to resolve this debate? Inner core rotation, if it exists, induces only slight travel time perturbations over the interval spanned by instrumental seismology. The key then is to analyze many data series over long time intervals. Much future research lies in the past. Just as long-term recordings in astronomical observatories detected the irregularities of mantle rotation, old records gathered over past decades in seismological observatories are essential for detecting inner core differential rotation. No definitive conclusion about inner core rotation will be drawn until a large number of these data can be processed, a task made difficult by the limited number of stations having run continuously for 30 years and having accessible archives.

Right now, the differential rotation of the inner core is not yet firmly established. Even if today's results are contradicted tomorrow, they represent an important step for deep-Earth science, because they have already provoked exciting questions in geomagnetism, seismology, and geodynamics.

References and Notes

1. X. Song and P. G. Richards, *Nature* **382**, 221 (1996).
2. W.-J. Su, A. M. Dziewonski, R. Jeanloz, *Science* **274**, 1883 (1996).
3. K. C. Creager, *ibid.* **278**, 1284 (1997).
4. A. Souriau, P. Roudil, B. Moynot, *Geophys. Res. Lett.* **24**, 2103 (1997).
5. P. Shearer, *J. Geophys. Res.* **99**, 19647 (1994); W.-J. Su and A. M. Dziewonski, *ibid.* **100**, 9831 (1995); S. Tanaka and H. Hamaguchi, *ibid.* **102**, 2925 (1997); D. W. Vasco and L. R. Johnson, *ibid.* **103**, 2633 (1998).
6. X. Song, *Rev. Geophys.* **35**, 297 (1997).
7. A. Souriau, *Geophys. J. Int.*, in press; A. Li, P. G. Richards, X. Song, paper presented at American Geophysical Union Spring Meeting, Boston, MA, 26 to 29 May 1998 [*Eos* **79**, S218 (1998)].
8. B. A. Buffet, *Nature* **388**, 571 (1997); B. A. Buffett and K. Creager, paper presented at American Geophysical Union Spring Meeting, Boston, MA, 26 to 29 May 1998 [*Eos* **79**, S218 (1998)].

9. I thank K. Feigl for critical reading of the manuscript. Inner core studies are supported in France by INSU/CNRS, "Intérieur de la Terre."

PERSPECTIVES: ATOMIC PHYSICS

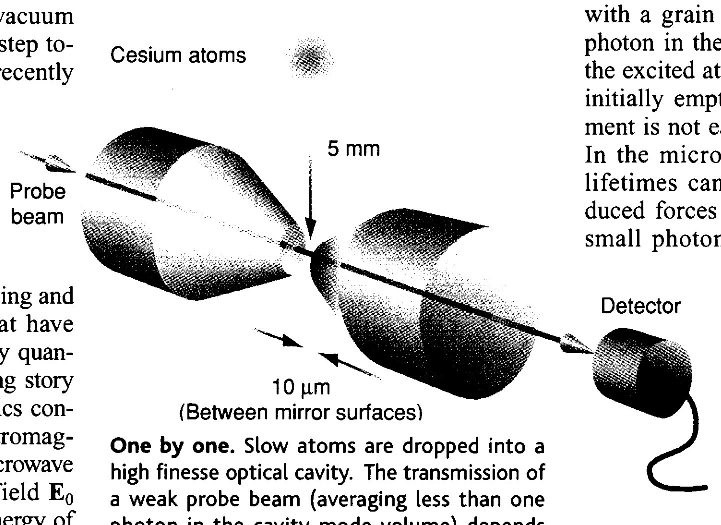
Under Control

Philippe Grangier

During recent years, the control of atomic motion with forces induced by light has grown into a research field of major importance and sophistication. As they push these techniques to the extreme, researchers are facing an open question: Is it possible to trap an atom into the field of one single photon, or even in the so-called "vacuum field"? An important experimental step toward addressing this problem was recently made by Hood *et al.* (*1*).

Enhanced online at www.sciencemag.org/cgi/content/full/281/5373/56

It may seem strange at first to speak about trapping atoms in the vacuum field, that is, in the absence of any light. Getting the right physical insight into this question requires consideration of not only the standard techniques of atom cooling and trapping but also the concepts that have been developed in the field of cavity quantum electrodynamics. To make a long story short, cavity quantum electrodynamics considers the situation where the electromagnetic field stored in an optical or microwave resonator is such that the electric field $\mathbf{E}_0$ corresponding to the ground state energy of the resonator mode is extremely large. The value of $E_0 = |\mathbf{E}_0|$ is obtained simply by noting that the electromagnetic energy $\varepsilon_0 E_0^2 V$ stored in the volume V of the cavity mode is equal to the energy of half a photon, $\hbar\,\omega/2$. Consequently, the coupling energy $\hbar\, g_0 = |\mathbf{D}\cdot\mathbf{E}_0|$ between an atomic dipole $\mathbf{D}$ and the field $\mathbf{E}_0$ can also be very large. Here, the relevant scale for a "large" coupling is set by the rates at which the energy is dissipated out of the system, either by spontaneous emission from the atom (rate γ) or by leaking out of the cavity (rate κ). The promised land in cavity quantum electrodynamics, often called "strong coupling regime," begins, therefore, when g_0 is much larger than both γ and κ.



One by one. Slow atoms are dropped into a high finesse optical cavity. The transmission of a weak probe beam (averaging less than one photon in the cavity mode volume) depends sensitively on the interaction between each individual atom and the cavity field. [Adapted from (*1*)]

A simple scheme to trap an atom into such a "vacuum" field was proposed a few years ago (*2*). Consider an excited atom entering a cavity where $g_0 >> \gamma$, κ. When the atom is within the cavity, one must describe the system by considering the coherent coupling between the atom and the cavity, which occurs at a rate g_0 much larger than the energy dissipation. In other words, the photon that is brought in by the atom is "ringing" between the atom and the cavity but does not belong to either of them. This atom + cavity system has its own energy levels ("dressed levels" in the jargon), and it can be shown that some of these levels correspond to an attractive atom-cavity potential. If the atom enters the right level—this can be done by an appropriate choice of the atom-cavity detuning—then it will be attracted to the cavity center. We note obviously that the name of "vacuum field trapping" has to be taken with a grain of salt: There is indeed one photon in the game, which comes in with the excited atom, even though the cavity is initially empty. However, such an experiment is not easy to do for several reasons. In the microwave domain, excited state lifetimes can be very long, but light-induced forces are very small owing to the small photon momentum. In the optical domain, forces are large, but the decay times are typically much shorter than the time it takes for an (slow) atom to cross the cavity. Then the photon is rapidly lost, and the force vanishes.

Present studies (*1*), therefore, consider the situation where the atom-cavity system is driven by a weak external field. Although the best way to implement that scheme is still under study, the question is certainly worth an experiment. Such an experiment requires not only a strongly coupled atom-cavity system but also the introduction of very slow atoms into the cavity. Slow atoms have many advantages indeed: They yield a long atom-cavity interaction time T, which is very useful for diagnostics, and they have a very small kinetic energy, which can "see" the shallow potential

The author is at the Institut d'Optique, 91403 Orsay cedex, France. E-mail: philippe.grangier@iota.u-psud.fr