GROUNDWORK
Furthering the Influence of Earth Science

Super-rotation of Earth's inner core and the structure of scientific reasoning

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INTRODUCTION

Recent confirmation that Earth's inner core rotates with respect to the mantle (cf. Zhang et al., 2005) presents a good case to highlight important aspects of the structure of observation and reasoning in geophysics, geology, and the physical sciences in general. In particular, it can help to clarify the relationship between theory and evidence. Determining the rotation of the inner core is a solution to a so-called "inverse problem" (Jacobs, 1987, p. 2). The defining characteristic of an inverse problem is the challenge of determining properties of an unobserved cause based on observed properties of the effect. This provides an opportunity to raise some worthwhile methodological questions.

The first question is about confirmation. How is solving an inverse problem different from other forms of confirmation in science? A second question is about the difference between explanation and description. Is an inverse problem distinct from common patterns of explanation—in particular those that explain observed effects in terms of their unseen cause? What, if anything, has been explained by the discovery of super-rotation? Or, is this a case of describing an aspect of nature without explanation?

And then there is a question of the empirical status of super-rotation. Is the image of the rotating inner-core a matter of observation (with information moving from outside in, from the physical world into our minds), or inference (with information moving from inside out, from ideas to implied situations in the world)? Following the flow of information in the case of super-rotation will shed some light on this difference.

SUPER-ROTATION

Earth's inner core is solid; it apparently also rotates a bit faster than the rest of the planet. Most recent evidence puts the super-rotation at 0.3° to 0.5° per year, or about one extra revolution each 900 years (Zhang et al., 2005).

The super-rotation was predicted by models that explain Earth's inherent magnetism (Glatzmaier and Roberts, 1996). Detecting the theorized rotation is an example of an inverse problem, in that it uses measured data of effects on the surface to draw inferences about the causes within. The problem has now been solved by analysis of seismic waveform doublets (Zhang et al., 2005). The super-rotation is said to be "confirmed by earthquake waveform doublets" (Zhang et al., 2005, p. 1357).

The evidence is in the recording of seismic waves from earthquakes that are more or less on the opposite side of Earth. Refraction of the waves at interfaces between mantle and core, and bending of the waves through material of varying density, lead to multiple paths from source to receiver. Some of the rays go through the inner core, some go around it, and these will have different arrival times.

The key is in noting that the difference in arrival times between the through-the-core and avoid-the-core rays changes steadily over time. It increases, meaning that the through-the-core waves are being delayed more and more. This is measured by comparing data from two earthquakes that occur at the same place but at significantly different times. This is a *doublet*, identified as happening at the same place by the similarity of waveform. For earthquake doublets separated by decades or more, the arrival-time difference increases as the time between events increases. This suggests that something is steadily changing in the relative conditions between the inner core and the mantle.

The explanation, the account of what is changing and thereby causing the increase in arrival-time difference, starts with the idea that the inner core is grainy, like wood, with the grain running more or less parallel to the axis of Earth's rotation. The speed of seismic waves will depend on their orientation to the grain. If the inner core turns with respect to the mantle, the orientation of the grain will change and the speed of a wave will change. This explanation was suggested by Kenneth Creager even before the doublet data: "The most likely cause of time-varying changes in structure within the Earth is that the inner core is rotating with respect to the mantle and that the elastic structure of the inner core is not axi-symmetric" (Creager, 1997, p. 1285).

The logic of the confirmation is noteworthy. It starts with theoretical prediction of arrival times using a model with a rotating inner core. The measured arrival times then match those predicted. This is exactly the form of reasoning often called hypothetico-deductive confirmation, and it is the foundation of most descriptions of scientific method. Deduce a prediction from a hypothesis, then observe the prediction to be true.

From the original geodynamic conjecture to the more direct evidence in waveform doublets, the arguments have the same logic. They are versions of an inverse problem, inferring parameters of the core based on surface data. They pivot on a

GSA Today, v. 20, no. 7, doi: 10.1130/GSATG90GW.1

premise in which data are predicted from aspects of a model of the core. That pivotal premise is a conditional of the form: IF the core has this feature, then the data will be such and such. In other words, IF model, then data; it is not IF data, then model.

Insofar as an inverse problem is about cause and effect, the key step in solving the problem is predicting measurable consequences of the cause. If the inner core rotates with respect to the mantle, then the difference in arrival times will steadily increase. The cause (super-rotation) is the antecedent, and the effect (arrival-time details) is the consequent. The "inverse" in an inverse problem refers to the direction of the logic. The ultimate inference, about the cause, has to work back against the conditional relation between cause and effect—the one that says, IF cause, then effect. The logic has to work back along the causal chain.

The logical challenge of an inverse problem is characteristic of the challenge of most scientific reasoning. We observe effects and work to figure out the details of the cause. Our models of causes are typically in terms of sufficient conditions for the effect. Theories and theoretical calculations can say what would lead to and explain what is observed, but they can rarely say that it is the only thing that could. That is, models of causes are not necessary conditions for the observed effects. There are always other possible explanations for the data.

The fact that there are other theories, perhaps not proposed or even imagined at this time, that would explain the data shows that what passes the tests now is always vulnerable to future refutation. What we call confirmation is neither foolproof nor to be based on an individual test. The confirmation of super-rotation—the reason to believe it is real—is not in the latest evidence but in the overall corroboration from independent evidence and reasoning. The geodynamic modeling of Earth's magnetic field suggests the faster rotation. The waveform-doublet data corroborate this. And a third source of information, measurements of free oscillation of the whole Earth, how Earth rings after a large seismic event, is consistent with super-rotation as well. The logic in this last case follows the pattern in which observations are predicted by the model and then subjected to a "hypothesis test" (Laske and Masters, 2003, p. 11). We can label different results as "observations" or "evidence" or "inference" or "detection" of inner-core rotation (Song, 2003, p. 54), but there is no important difference in the logical structure or status. No particular case is the confirmation of the rotation by virtue of being more direct. The credibility of the hypothesis derives from the agreement among the different kinds of data.

CONCLUSION

The super-rotation of the inner core explains the details in differential arrival times of seismic waves from very distant earthquakes. In this way, solving the inverse problem is explanatory. In general, the model of a cause explains the observed effects, and by doing so, the model gains credibility. The logic in this case is the same as the logic of confirmation; the cause implies (and thereby explains) the observed effect.

The logic of an inverse problem is essentially the logic of hypothetico-deductive confirmation; the hypothesis implies observable effects. In no case is the evidence conclusive proof of a hypothesis. The more realistic assessment of scientific reasoning acknowledges that the credibility of a hypothesis accumulates as it fits into broad agreement with a variety of sources, both empirical and theoretical. The hypothesis of super-rotation fits the theoretical models of Earth's magnetic dynamo. It fits the empirical data of global free-oscillations. And it fits the more particular empirical data of wave-form doublets. This exemplifies what the philosopher of science, Karl Popper, called corroboration, "the degree to which a hypothesis has stood up to severe tests, and thus 'proved its mettle'" (Popper, 1965, p. 251). A severe test requires the hypothesis to entail observable data, and the test is survived when the data are in fact observed. The logic of Popper's corroboration is precisely the logic in the case of the rotation of the inner core.

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Manuscript received 5 Feb. 2010; accepted 26 April 2010.