

WHAT IS EARTH? ¶ POETS SAY IT'S A CELESTIAL SAPPHIRE, A CERULEAN orb. Astronomers say it's a medium-size planet orbiting an average star. Some environmentalists say it's Mother. Biologists say it's life's only known home. ¶ But the most scientifically precise definition may prove to be the one that no one suspected. Earth, says geophysicist J. Marvin Herndon, is a gigantic natural nuclear power plant. We live on its thick shield, while 4,000 miles below our feet a five-mile-wide ball of uranium burns, churns, and reacts, creating the planet's magnetic field as well as the heat

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# NUCLEAR PLANET

Is there a five-mile-wide ball of hellaciously hot uranium seething at the center of the Earth?

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that powers volcanoes and continental-plate movements. Herndon's theory boldly contradicts the view that has dominated geophysics since the 1940s: that Earth's inner core is a huge ball of partially crystallized iron and nickel, slowly cooling and growing as it surrenders heat into a fluid core. Radioactivity, in this model, is just a supplementary heat source, with widely dispersed isotopes decaying on their own, not concentrated. →

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**OPPOSITE:** The theory that Earth's inner core is a nuclear reactor has been greeted mostly with silence by many geophysicists, but J. Marvin Herndon insists: "Eventually, the evidence will accumulate to the point where it cannot be ignored."



By Brad Lemley

Photograph by Dan Winters and Gary Tanhauser

If Herndon's theory is true, it would be the biggest news in geophysics in decades. "I would rank it right up there with plate tectonics as one of the truly great discoveries," says Hatten Yoder, director emeritus of the Geophysical Laboratory of the Carnegie Institution of Washington. The idea also has immediate implications for human beings and all other living things on Earth. While it leaves open the question of whether nuclear fission is a sensible way to make power, it does at least mean that fission is a natural, even essential process. "We owe our very lives to it," Herndon says. That subterranean nuclear reaction, he says, is the dynamo that powers Earth's magnetic field, which protects us from the ravages of the sun.

"Solar radiation would have stripped off our atmosphere long ago without the repulsion provided by the field," says nuclear engineer Daniel Hollenbach, Herndon's collaborator at the Oak Ridge National Laboratory. "We absolutely depend on it."

Herndon recently put forth what he sees as the most compelling argument for his theory in a paper published in the *Proceedings of the National Academy of Sciences*. Using computer simulations that Hollenbach helped him run at Oak Ridge, Herndon showed how software that tracks fuel usage at nuclear power plants indicates that a "planetary-scale georeactor" could indeed have been blazing away for 4.5 billion years, the widely accepted estimate of Earth's age, at heat levels that match Earth's actual output of roughly four terawatts. Moreover, such a reactor would vary in intensity—sometimes strong, sometimes weak, sometimes shutting down altogether—which could explain why Earth's magnetic field has periodically waxed, waned, and reversed through the millennia.

Herndon contends that not only does Earth probably have a reactor boiling at its core but so do Jupiter, Saturn, and Neptune. Natural nuclear reactors could explain a lot of mysteries, from how stars ignite to the nature of dark matter, the mysterious, elusive stuff that astronomers say is 10 times more common than the ordinary matter they can observe. Indeed, Herndon's theory, if correct, would require nothing less than revamping our view of how much of the material universe operates.

"It's an idea with a lot of explanatory power," he says.

Perhaps.

In the geophysical community, Herndon is stranded on his own tectonic plate. According to the dominant core theory, the magnetic field is powered by the dynamolike vortices of molten iron and nickel swirling around a solid iron-nickel ball, not—as Herndon contends—by flows of charged particles surrounding a blazing nuclear reactor. While Herndon has pushed the premise for 11 years and published papers in impressive journals, including the *Proceedings of the Royal Society of London*, his work is seldom cited by other geophysicists. His theory is not so much refuted as ignored.

"The data just does not demand it," argues Bruce Buffett of the University of British Columbia, who says he has read one of Herndon's early papers. You can run numerical simulations of convection with the traditional models, he says, and get the kind of magnetic-field behavior that shows up in the geologic record. "What he is doing sounds like a line of reasoning, not a proof."

Still, Herndon is not without prominent champions. "Many paradigms that we follow today don't have as much backing

as he has put together for this," says the Carnegie Institution's Yoder. "He has a fresh new idea, and he has fit it all together extremely well. We need to consider what he has to say."

So Herndon's story, like that of iconoclasts who have walked a similar path before him, may not be just a debate over what's happening in Earth's core but a tale of how revolutionary theories can be frozen out of scientific debate. Herndon, soft-spoken by nature, grows agitated when he considers the battle he has waged. "I would be delighted if there were a raging controversy over this," he says. "Scientists depend on funding, and they become frightened of anything controversial."

"He has a hard time getting attention," adds J. Freeman Gilbert, professor emeritus of the Institute of Geophysics and Planetary Physics at the University of California at San Diego. "This should not be a society of censorship."

J. MARVIN HERNDON IS 58 YEARS OLD, TALL AND BROAD, WITH A gentle voice and a meticulous way of speaking: "Logical" and "step by step" are two of his favorite expressions. He lives and works in the upscale San Diego suburb of Scripps Ranch, in a home full of antiques: Japanese *tansu* chests, salt-glazed Georgian pottery, and iridescent Depression glass, all carefully arranged and dusted. He is married to a computer scientist, and they have three grown sons. Independent scientific investigation is something of a family trait. The youngest son, Christopher, published his first paper, on unnatural causes of death among Roman emperors, when he was 12 years old.

Herndon earned a doctorate in nuclear chemistry from Texas A & M University in 1974. From 1975 through 1978, he was a postdoctoral student at the University of California at San Diego under Harold Urey, winner of the 1934 Nobel Prize in chemistry, and Hans Suess, developer of the carbon 14 dating method. "These guys were giants in their fields. They really taught me how to do science," Herndon says. But only a year after accepting a research position at UCSD, Herndon quit. "I was starting to find out some interesting things about the composition of Earth's core. But it became clear to me that if I stayed in the academic community, I would have to toe the line and work on other people's models." Although Herndon had not formed his theory back then, he did believe—and still does—that much of Earth's inner core is not iron-nickel but a nickel-silicon compound called nickel silicide.

Inge Lehmann, the famed Danish geophysicist who in 1936 discovered that Earth has a solid inner core, found Herndon's published papers on the concept compelling. "I admire the precision of your reasoning based on available information, and I congratulate you on the highly important result you have obtained," she wrote him in 1979. But the theory was otherwise shunned. "It was like an iron curtain fell down. I chose to leave, but I resolved to keep working on the idea, paying for it out of my own pocket," Herndon says. For the next 24 years, he worked as a mining consultant. But rather like a slowly building nuclear reaction, the pile of evidence for something radically different going on at Earth's center accumulated on his desk, growing toward critical mass.

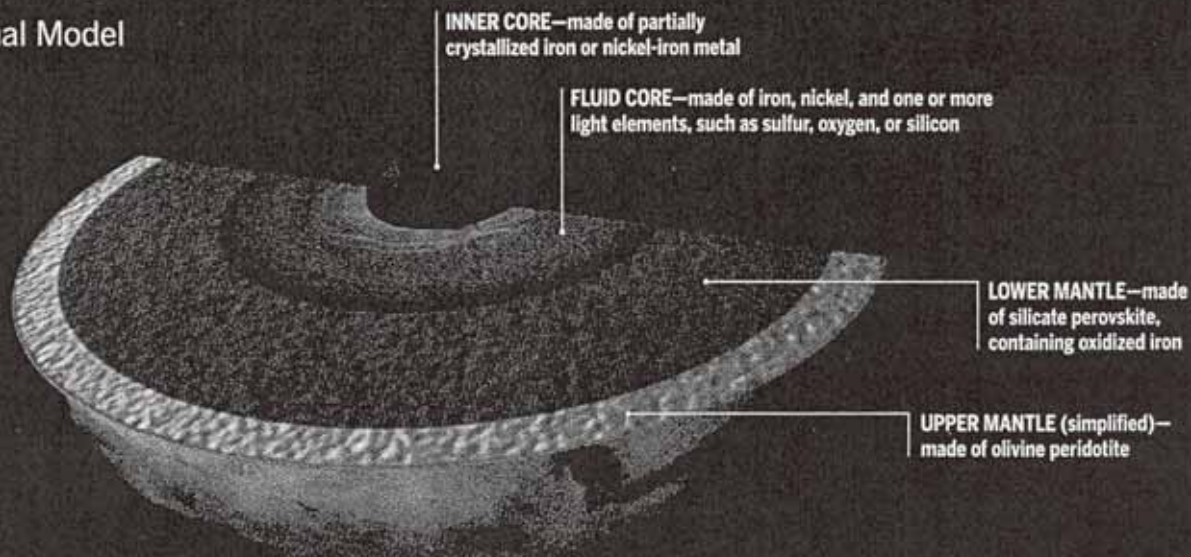
The first piece of evidence came from a mine in Gabon, Africa, where in 1972 French scientists found fission-produced

# The Core Dispute

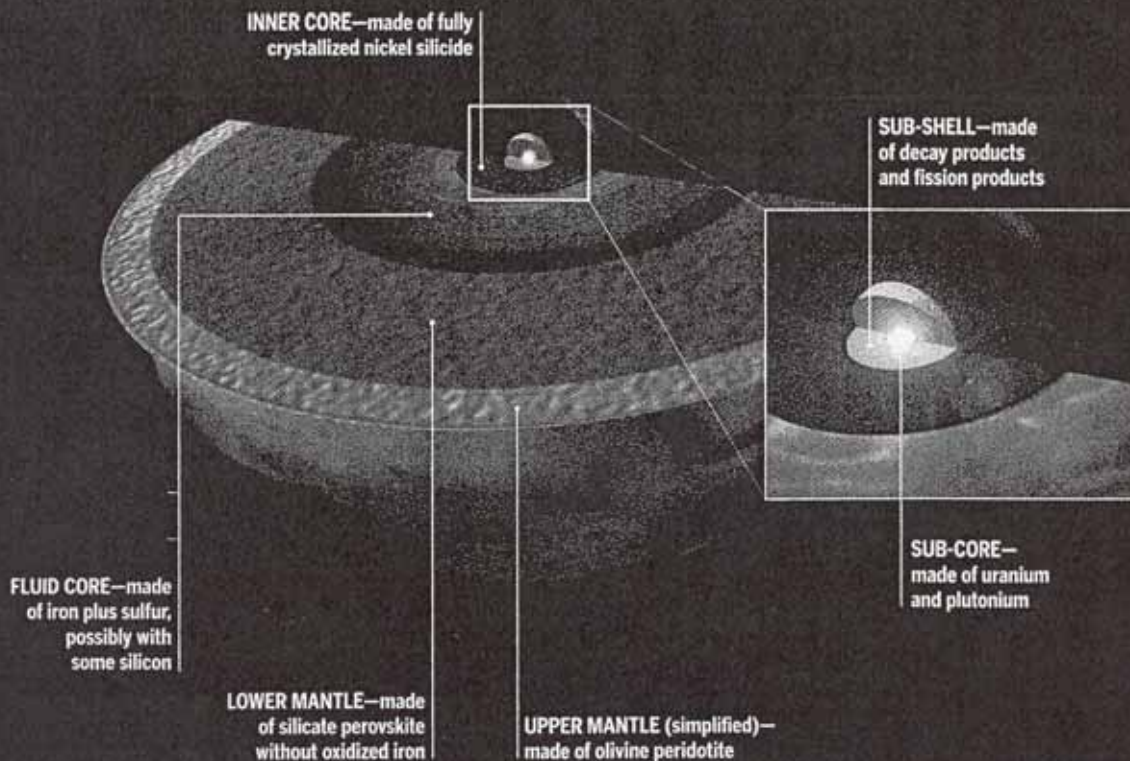
The prevailing theory among geophysicists is that a ball of iron and nickel at Earth's center slowly grows as it releases heat into a fluid core (top diagram). In Herndon's model (bottom diagram),

a natural fission reactor composed of uranium and plutonium is surrounded by a nickel-silicon compound known as nickel silicide. Herndon's model also includes some variations in the elements at the core-lower mantle boundary.

## Traditional Model



## Nuclear Earth Model



Graphic not to scale

## If giant planets like Jupiter could have nuclear power plants at their cores, he reasoned, why not Earth?

isotopes of neodymium and samarium in a seam of uranium. The uranium, they realized, had functioned as a natural nuclear reactor for 200 million years before exhausting itself 2 billion years ago. Subsequent investigation found several similar natural-fission sites in the area. "I first heard about that when I was a graduate student, and I knew it was important," Herndon says. "Curiously, the subject appears never to have been addressed in the pages of *Science* or the *Journal of Geophysical Research*," he wrote in a 1998 paper published in *EOS*, the journal of the American Geophysical Union.

Another fuel rod in Herndon's reactor was the 1960s discovery that Jupiter's albedo, or brightness, indicates that the giant planet radiates into space about twice as much energy as it receives from the sun. Later, Saturn and Neptune were found to give off similarly large quantities of energy. The phenomenon is "one of the most interesting revelations of modern planetary science," wrote William Hubbard, who is professor of planetary sciences at the University of Arizona's Lunar and Planetary Laboratory. Hubbard ruled out radioactivity and fusion reactions as too weak to cause the effect.

In 1990 Herndon's middle son, Joshua, told him about Jupiter's excess energy production, a fact he found in the book *The New Solar System*, edited by J. Kelly Beatty and Andrew Chaikin. "Three weeks later, in the grocery store of all places, the answer suddenly hit me," says Herndon. "Jupiter had all the ingredients for a planetary-scale nuclear reactor. I immediately started looking through the literature, thinking someone must have come to the same conclusion already." He pauses, shaking his head as he watches an Anna's hummingbird sip from a fountain in his cactus garden. "No," he says. "Nothing."

Herndon did the calculations, wrote up the idea in a paper called "Nuclear Fission Reactors as Energy Sources for the Giant Outer Planets," and published it in the German science journal *Naturwissenschaften* in 1992. It has since met with deafening silence. "I wish someone would respond, tell me that the science is wrong, but I just get nothing," he says.

Undaunted, Herndon subsequently turned his attention earthward. If the giant planets could have nuclear power plants at their cores, he reasoned, perhaps this little one could as well. "It would answer a lot of questions," he says.

One of the most mysterious aspects of Earth's magnetic field is that once every 200,000 years, on average, it reverses. It also periodically grows weak, then strong again. This is not just theory. The magnetic field's meandering history is indelibly inscribed in rocks: Ferrous minerals, especially magnetite, in one stratum show strikingly different orientations from those in another.

In Herndon's view, these polarity flip-flops make no sense if the magnetic field is powered, as traditionalists contend, by heat from the crystallization of molten iron and nickel from the fluid core or from the decay of isolated radioactive isotopes. "Those are both gradual, one-way processes," he says. But if the field's energy results from a mass of uranium and plu-

tonium acting like a natural nuclear reactor, Herndon says, such variations in the field's strength would be almost mandatory.

Instead of an iron-nickel ball about seven-tenths the diameter of the moon, imagine a natural nuclear reactor at Earth's center, consisting of a five-mile-wide sphere of uranium 235 and uranium 238. This would be what nuclear engineers call a fast-neutron breeder reactor, making energy from both uranium and fissionable plutonium created by the reactor itself. And instead of a surrounding sphere of liquid iron and nickel, imagine one made of solid nickel and silicon, melded into nickel silicide. As the reactor fissions inside this nickel silicide sphere, Herndon believes, it produces heat that propels charged particles, which ultimately produce the magnetic field.

How would that field vary? Nuclear fission creates by-products that absorb neutrons, slowing the reaction. Eventually, such reactor "poisons" could even halt the process. But those by-products, being lighter than the uranium-plutonium mix, would also tend to slowly float out to form a shell around the fissioning ball. After a while, enough would leave the ball so that the uranium could begin reacting again. "This time, the geo-reactor might increase in power and cause the magnetic field to grow, either in the same direction or in a reverse direction," says Herndon. "It's a very nonlinear process."

Geophysicists contacted for this story conceded that alternatives to the mainstream scenario are possible: The cooling iron-nickel-ball inner core, they admit, is still just a theory, if a dominant one. But they had one major objection to Herndon's proposal. How, they asked, during Earth's formation could all of that uranium have clumped in the center? Silicates, they say, tend to bond with uranium, making a lighter-weight compound that would resist sinking to the center of the young Earth. "Radioactive isotopes tend to get bound up with the silicates" and

### Shine on, radioactive moon

The moon may appear cold and dark to earthbound observers, but NASA scientists announced in February that the lunar interior appears to be hot and molten, a finding that Herndon says lends support to his natural-reactor theories. Researchers at NASA's Jet Propulsion Laboratory in Pasadena, California, used laser reflectors, installed on the moon's surface by astronauts 30 years ago, to determine that the moon expands and contracts by up to four inches every 27 days. This tidal distortion, caused by gravitational pull from Earth and the sun, indicates that the moon's innards are at least partially molten. The finding was not a complete surprise. Moonquake waves, measured during Apollo missions, lost energy if they traveled deeper than halfway to the moon's center—another indication of a molten interior. "When you have a small object producing a lot of energy, that's very suggestive of fission at the core," says Herndon, who is also intrigued by Io, a small yet extremely volcanically active moon of Jupiter. "I think both of those moons have small reactors inside of them." —B.L.

## Clues about the makeup of Earth's inner core dwell inside stony meteorites called chondrites

dispersed throughout Earth's crust, argues University of British Columbia geophysicist Bruce Buffett. "The concentration, to me, just doesn't sound plausible."

The answer, says Herndon, dwells inside chondrites, stony meteorites that have fallen to Earth and are thought to represent a record of conditions during the solar system's birth. "Most of today's geophysics is based on the idea that Earth is like ordinary chondrites, which were formed under relatively oxygen-rich conditions," he says. But there is a small group of meteorites called enstatite chondrites that formed under conditions in which much less oxygen was present. "These are like the inner planets," Herndon says. "The oxygen isotopes in enstatite chondrites are identical to what we find inside Earth."

Herndon says enstatite chondrites most closely correspond to Earth's composition and show how uranium can concentrate. "When there is plenty of oxygen, all of the elements that like to combine with oxygen would go with the silicates. But when there is limited oxygen, elements such as uranium and magnesium would in part go to Earth's core," he says. He estimates that 64 percent of the planet's uranium sank to Earth's center this way—more than enough to begin a reaction.

Herndon's most important piece of physical evidence comes from the composition of Hawaiian basalts. Seismologists think these basalts spewed from a heat source that lies deep within Earth, perhaps near the boundary of the outer core. In Herndon's natural-reactor theory, the lava that birthed the basalts would not be radioactive because the heavy uranium could not flow up from Earth's inner core. But a relatively light element such as helium could easily make the 4,000-mile vertical journey to Earth's surface, bearing with it signs of nuclear fission.

"People have for 32 years observed helium with a mass of 3, as well as helium 4, in these basalts," Herndon says. "Helium 4 is not a surprise; it comes from the natural decay of uranium

and thorium. No fission need be involved. But helium 3 is a big surprise. It's a fission by-product. No one knows how it could be made deep in the Earth. People think it must be left over from planetary formation." He pauses. "No way. In the simulation we ran at Oak Ridge, we came up with a ratio of helium 3 to helium 4. Those numbers could have been anything, any ratio. But they turned out to be right in the range of the values observed in these basalts." He looks up. "This ratio is compelling evidence. It knocked my socks off."

The ratios particularly excite Hatten Yoder. "The helium results he has are extraordinary—it just fits the theory so well. I would like to see him get the data for [fission-produced isotopes of] neon. If he gets the right ratio there as well, that would be another big nail. I just don't see how people could ignore it then."

Herndon is working on that calculation now.

If geophysics at least acknowledges the possibility of natural fission, Herndon says, it could help illuminate far more than just the conditions within planets. Mainstream astrophysics holds that as gravitational collapse concentrates and heats matter, it kicks off the fusion reaction that makes stars shine. But direct evidence for the generation of sufficient heat has been difficult to find. Herndon believes the answer to stellar ignition may be "a nuclear fission trigger," he says. "It's a concept that has been proven experimentally with the detonation of every hydrogen bomb." And if fission ignites stars, star-size bodies that lack a critical mass of fissionable elements might never light up, which would help explain the mystery of dark matter. Herndon notes that astronomers have theorized that dark matter is particularly abundant around stars with very little metal content. Dark matter, he says, may be made of star-size spheres that lack metallic elements that are capable of fission. No fission, in his view, would mean no fusion; the huge spheres would remain forever dark.

The next step in proving his theory about Earth's composition, says Herndon, requires some basic materials science and should involve other researchers equipped with a diamond anvil—a high-temperature, high-pressure crucible geoscientists use to see how minerals behave under inner-core conditions. They could test whether the nickel-silicon compound Herndon thinks makes up most of Earth's inner core is stable at pressures that would be found in the center.

A gentle San Diego winter day has mellowed into dusk. Herndon lives at the edge of a leafy park; his deck gets the dappled shade of wild pepper, pine, and eucalyptus trees. It's a comfortable, even sybaritic setting, but Herndon does not seem to see it.

"I have done everything so far out of my own pocket," he says, looking across the green valley. "I am one man, and I've made progress, but there is more to do. It's an idea that can be investigated. It needs rigorous examination, a real debate."

Herndon smiles. "People who challenge the orthodoxy sometimes seem a little nutty. I may be nuts for putting so much energy into this, but the theory itself is not nutty at all." ☐

### Is Earth approaching meltdown?

If Earth has a natural nuclear reactor blazing away at its core, how much longer might it remain active? The question isn't merely academic. The reactor, Herndon believes, powers Earth's magnetic field, which shields its inhabitants from deadly solar radiation.

The answer is a bit worrisome. According to the simulation Herndon performed at the Oak Ridge National Laboratory, about 75 percent of the uranium has been burned up in the 4.5 billion years of Earth's existence. That means the uranium sphere has shrunk from about eight miles in diameter to five miles. At the power level that Herndon regards as most likely—roughly four terawatts—he calculates that the reaction could end in 2 billion years or less. That compares unfavorably with the traditional iron-core model of Earth's interior, which by some estimates leaves us with another 4 billion years of protective shielding.

"The nuclear fission reactor gives us a much shorter time frame than geophysicists have traditionally believed," says Herndon. —B. L.