

# The Centers of Planets

*In laboratories and computers, shocked and squeezed matter turns metallic, coughs up diamonds and reveals Earth's white-hot center*

Sandro Scandolo and Raymond Jeanloz

Those who enjoy following planets in the night sky got a special treat this summer as Mars passed nearer to Earth than it had come in 60,000 years. Even at close range, though, the Red Planet retained an air of quiet mystery. All the planets have it: In contrast to the twinkling stars around them or the lights of the noisy city, the planets appear peaceful and immobile. And in fact planets *are* mysterious; in some ways we know little more about them than did the ancients who worshiped them. In particular, we have few clues as to what any of the planets (even our own) are like on the inside.

What we do know is that the interior of a planet is not a peaceful place. From the evidence that exists, we can infer that the interiors of planets typically are subjected to pressures more than a million times that of Earth's atmosphere at the surface and that temperatures in their centers reach several thousand degrees Celsius. You can

think of each planet's interior as a giant foundry specialized for processing a particular chemical composite under extreme conditions. These composites range from the simple hydrogen-helium mixture of Jupiter and Saturn to the more complex mixture of "ices" (water, ammonia and methane) that compose Neptune and Uranus, and finally to the mostly "solid" internal structures (silicates plus iron in solid and sometimes liquid form) of terrestrial planets such as Mars, Venus and of course Earth. "Solid" here is a bit of a stretch; over geological time planetary-scale objects made of rock, metal or ice deform and exhibit convection just as fluids do. Likewise the substances we call ices are not strictly solid; they exist as gases in the outer atmospheres of giant planets and as fluids in the interior.

The interiors of planets are totally inaccessible, so what we know comes from indirect measurements and analysis. For example, seismic waves detected at the Earth's surface tell us a great deal about the internal structure of our planet. Similarly, measurements of mass, gravitational moments (variations in the strength of gravity at different positions above and around a planet), magnetic fields and a few other quantities, taken by space probes or remote observation, allow us to infer the density profiles and internal dynamics of all the planets of the solar system. Estimating pressure is a fairly straightforward matter because we have reliable equations to calculate pressure from mass and depth—the same equations that tell a deep-sea diver how fast pressure will increase during a descent. Surface observations—for example, the chemical makeup and thickness of the atmos-

phere—can shed further light on the composition of a planet.

Unfortunately the information one gets is only enough to make crude estimates. And it is hard to imagine a probe capable of penetrating the skin of a planet to a depth of more than a few miles and bringing back a sample of material from the interior. In its 1996 encounter with Jupiter, the Galileo probe made a successful 600-kilometer-deep dive into the giant planet, revealing unexpected features of the outer layers. But 600 kilometers is a scratch on the surface of Jupiter, whose radius is 70,000 kilometers. The deepest anyone has ever drilled into the Earth is 12 kilometers, just 0.2 percent of the distance to the center. And there is every reason to expect that the samples from such limited probes may not be representative of the planetary interior.

Frustrated by the lack of concerted effort to send probes into the deeper regions of the Earth, David Stevenson at the California Institute of Technology recently made a "modest proposal." He

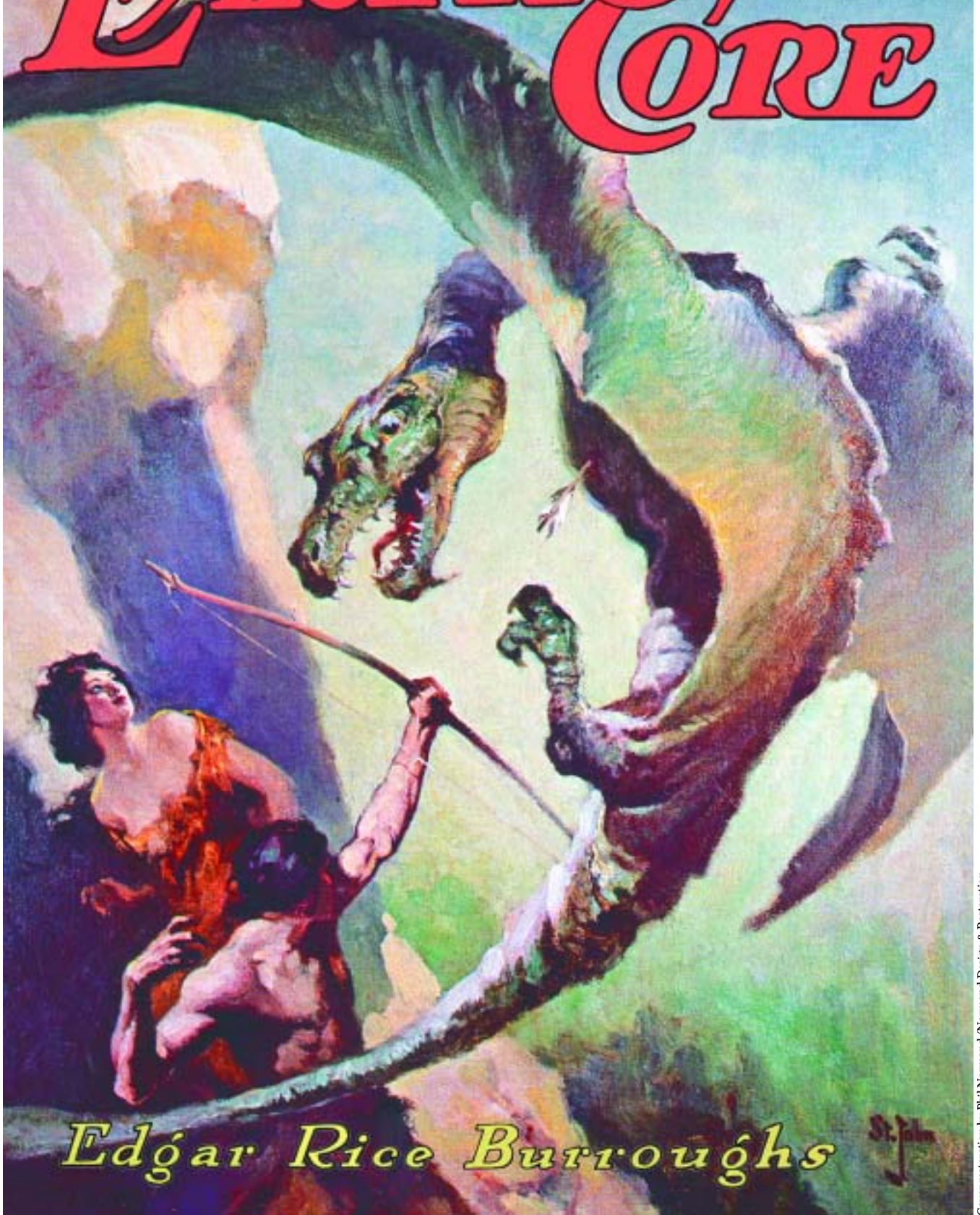
**Figure 1.** What lies at the center of Earth? The public imagination has freely explored the places that scientists cannot. Edgar Rice Burroughs, best known as the father of Tarzan, was one of many authors who have created imaginary worlds beneath our feet. This book jacket imagines life in Pellucidar, a "world at the Earth's core" that figured in seven novels written between 1913 and 1944. In Burroughs's conception, the Earth's crust is only 500 miles thick, leaving a vast hollow interior accessible via an opening near the North Pole. This "savagery of unspoiled Nature" is inhabited by dinosaurs, huge mammals and a variety of intelligent native races. A rather different picture of Earth's core emerges from experiment and external measurements, but much remains unknown about the centers of our planet and others.

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*Sandro Scandolo was recently appointed senior staff member at the Abdus Salam International Centre for Theoretical Physics (ICTP) in Trieste, Italy, where his research encompasses simulations of high-pressure phase transitions in covalent, molecular and metallic systems in addition to surface science, polymers and nonlinear optics. He received his Ph.D. in physics from the Scuola Normale Superiore in Pisa in 1993. He then moved to the International School for Advanced Studies (SISSA) in Trieste, where he became assistant professor in 1998 and associate professor in 2002. He spent a two-year sabbatical leave (2000–02) at the Princeton Materials Institute, Princeton University. Raymond Jeanloz is professor of Earth and planetary science and of astronomy at the University of California, Berkeley, where his group studies the nature and evolution of planetary interiors, as well as the properties of materials at high pressures. Address for Scandolo: Abdus Salam ICTP, Strada Costiera 11, I-34014 Trieste, Italy. Internet: scandolo@ictp.trieste.it*

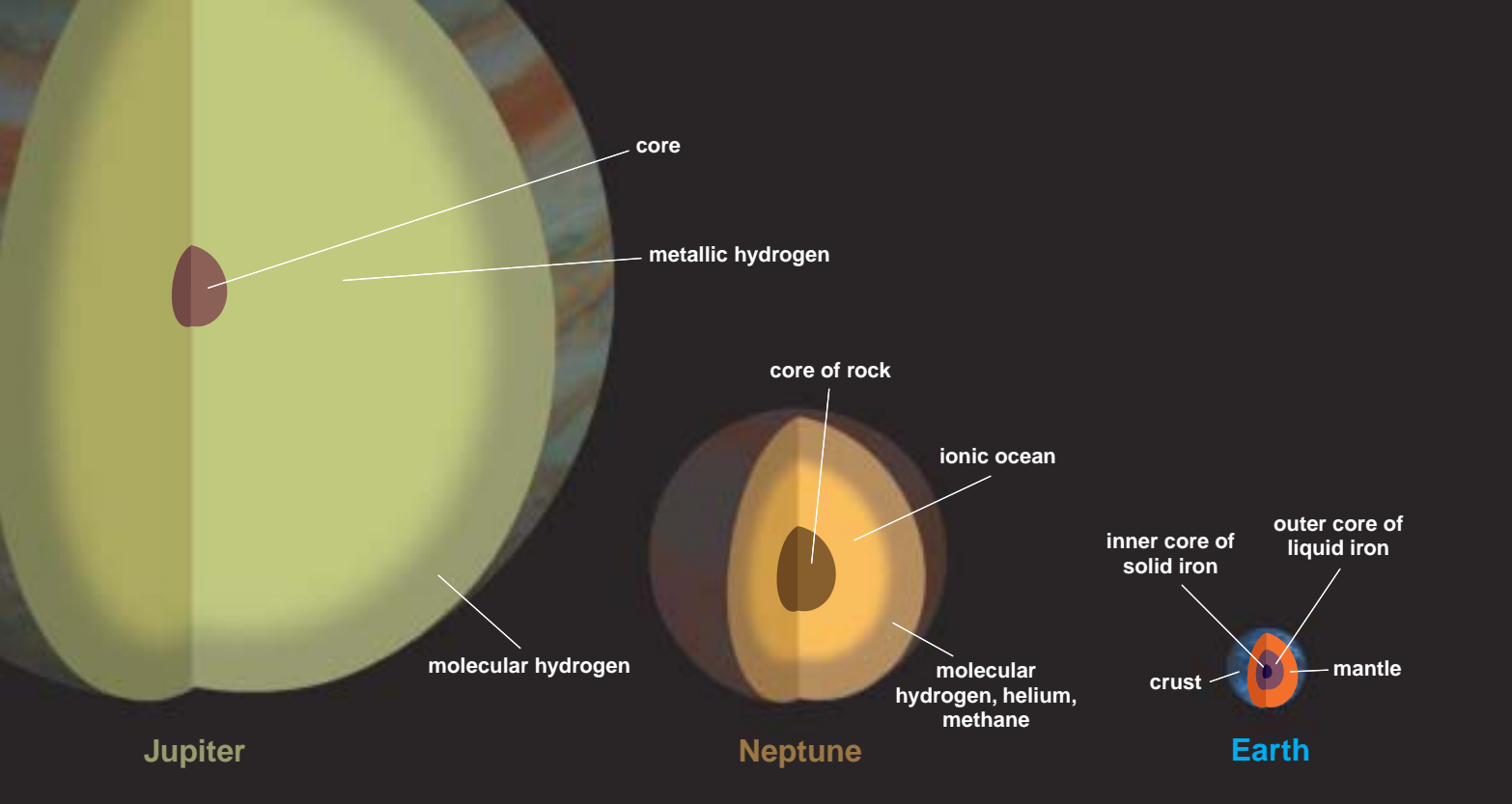
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# AT THE EARTH'S CORE



*Edgar Rice Burroughs*

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**Figure 2.** Jupiter and Saturn, the solar system’s gas giants, are known to be composed of the simplest element, hydrogen, mixed with some helium, but recent experiments have confirmed that under high-pressure conditions hydrogen becomes a metallic fluid. Jupiter’s center is thought to contain a core of rock at extreme pressures. The composition of Uranus and Neptune is richer, including water, ammonia and methane. Experiments and simulations in this case suggest that these molecules dissociate, creating an ionic ocean between the gaseous outer layer and solid core. Finally, Earth holds membership in the terrestrial planets, where a mantle of silicate and oxide rock gives way to a mostly iron core that, in the case of Earth, has a solid inner core surrounded by a liquid outer core.

claims that with a fraction of the financial outlay required to launch a space mission, a million tons of liquid iron could be poured into an artificial fracture at the Earth’s surface. The iron would slowly but inexorably dive toward the Earth’s center, and it could carry along insoluble probes that would send first-hand information from the bowels of the planet. With his tongue-in-cheek suggestion, Stevenson has captured the frustrations of geophysicists eager for ways to plumb the deep mysteries of planets.

Stevenson is also not the first scientist to reach for creative solutions. In fact, a large international community is exploring a completely different approach to the study of planetary interiors. Instead of trying to gain direct access to Earth’s inner workings, some scientists have been striving since the early 20th century to simulate the conditions of pressure and temperature that shape planetary interiors. Micro-worlds created in the laboratory open a spectacular window into the composition, dynamics and evolution of planets, and may even offer a glance into the history of the solar system and how it evolved to its present form.

It is not easy to produce pressures of a million atmospheres and temperatures of a few thousand degrees inside the walls of a laboratory, let alone sustain them in a controlled way to allow sufficient time for measurement. Fortunately experiments can be complemented by theoretical calculations grounded in quantum and statistical mechanics, which can simulate from first principles the conditions existing deep inside planets.

### Diamonds Are Not Forever

In the dark rooms of the Geophysical Laboratory at the Carnegie Institution of Washington, Dave Mao and Russell Hemley are getting closer each day to being able to reproduce in a controlled way the extreme conditions found in planetary interiors. Mao and Hemley are leaders in the use of cells that use diamond anvils to create extreme pressures (see “The Diamond-Anvil Cell,” May–June 1992). As the hardest known material, diamond is well suited to the task of squeezing substances to a few million times atmospheric pressure.

To carry out the job, a pair of brilliant-cut gems, each usually weighing about one-quarter of a carat, is embedded in a

powerful press. Unfortunately, the higher the pressure exerted by the pistons and screws, the greater the chance that one of the two diamond anvils that compress the sample—each typically a few millimeters in diameter—will fail, causing the experiment to implode suddenly with a single loud blast.

Mao reckons that he has broken hundreds of diamonds—small ones, fortunately. But the dismay caused by the occasional failure of a diamond is more than matched by the thrill of the amazing discoveries that have been made possible by this tiny device. When diamonds do withstand the load to which they are subjected, the pressure that can be reached at the center of the anvil’s tip, a spot a few tens of micrometers large, is enough to reproduce the conditions found along a considerable fraction of a planetary radius.

Squeezing matter to planetary pressures dramatically alters its macroscopic properties, including some that are essential in planetary modeling: density, mechanical strength, viscosity and electrical conductivity. Substances can change their state under extreme pressure; for example, water and many other liquids solidify. In rarer instances

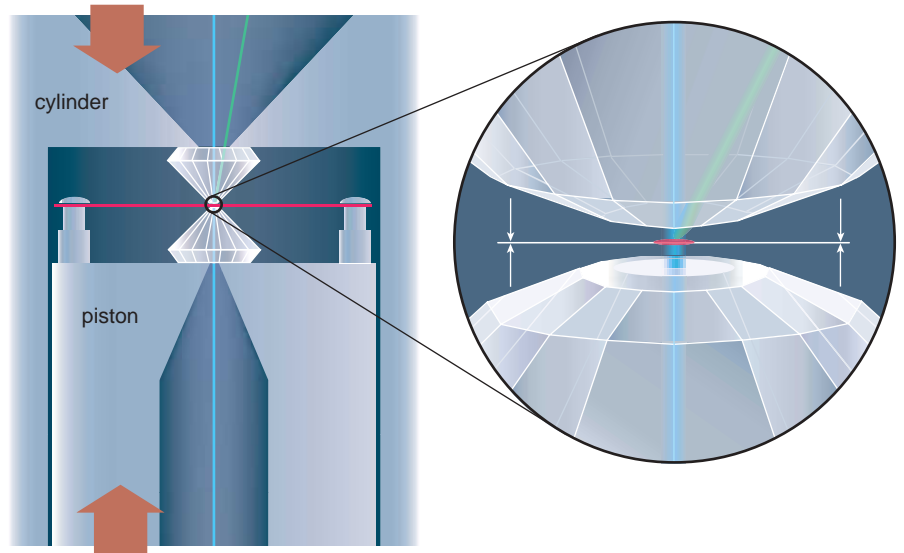
the reverse can happen. Solids can transform from one crystal structure to another in order to optimize the packing of atoms. Transparent salts turn into black metals. Magnetic materials such as iron lose their magnetism. The higher the pressure, the longer the list of surprises. Put another way, under extreme pressure chemical bonding is profoundly changed, such that a completely new periodic table emerges: Potassium becomes a transition metal and oxygen a superconductor.

The work of Mao and Hemley is part of a resurgence of interest in high-pressure experiments. They are members of a second generation of investigators in a field that was believed to have reached its maturity more than 50 years ago with the Nobel prize awarded in 1946 to pioneer Percy W. Bridgman. Hundreds of substances had been compressed in Bridgman's ingenious apparatus, up to pressures exceeding 100,000 atmospheres. Bridgman's successors have achieved new results both with static-compression methods, such as the diamond-anvil cell, and also with the refinement of dynamic-compression methods based on shock waves. As soon as new record pressures are announced, new and surprising phenomena are discovered. In 1976, Mao and Bell broke the one-million-atmosphere barrier. Breaking the barrier was not merely a symbolic event. It meant they were able to reproduce the pressures at the bottom of the Earth's mantle and deep inside the giant planets.

### Metallic Hydrogen

Back in 1935, Eugene Wigner, one of the founding fathers of quantum mechanics and at the time a professor at Princeton University, suggested that hydrogen, an inert molecular gas at ambient conditions, could turn into a metallic solid, similar to lithium or sodium, at sufficiently high pressure. Wigner's proposal implied a remarkable complexity for "element one," the simplest chemical entity, one electron bound to one proton.

Because hydrogen is known to make up about 90 percent of the volume of Jupiter and Saturn, the appearance of a metallic state of hydrogen at high pressure could seriously alter our understanding of planetary interiors. Planetary and stellar magnetic fields are generated through a dynamo-like mechanism by electrical currents in the metal-



**Figure 3.** Diamond-anvil cells squeeze tiny samples of matter between a pair of gems at pressures close to those known to exist in planetary interiors—millions of times Earth's atmospheric pressure. In the device, which is about the size of a standard box of tissues, pistons and screws apply pressures that are sometimes great enough to fracture diamonds, the hardest known material. A laser or x-ray beam (blue) is scattered (green) to read detailed information from a tiny sample, detecting alterations in the material that are often dramatic.

lic regions of their interiors. Earth's magnetic field, for example, originates in the liquid metallic outer core. Jupiter's magnetic field, first measured by Voyager spacecraft, is ten times stronger than Earth's, and its pattern is considerably more complex. Part of this complexity could be accounted for if the source of the field lay much farther from the center, in relative terms, than does Earth's. Wigner's prediction of metallic hydrogen was based on a simplified analysis of the electronic ground state, but the pressure he calculated for the transition to the metallic state, about 250,000 atmospheres, corresponded to a depth of less than one-twentieth of the planetary radius of Jupiter. In other words, most of the solar system's largest gas giant had to be in a metallic state—although the metallic hydrogen would have to be a fluid rather than a solid to provide dynamo action.

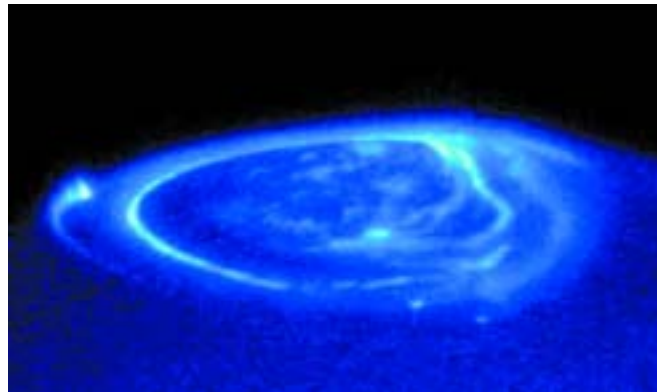
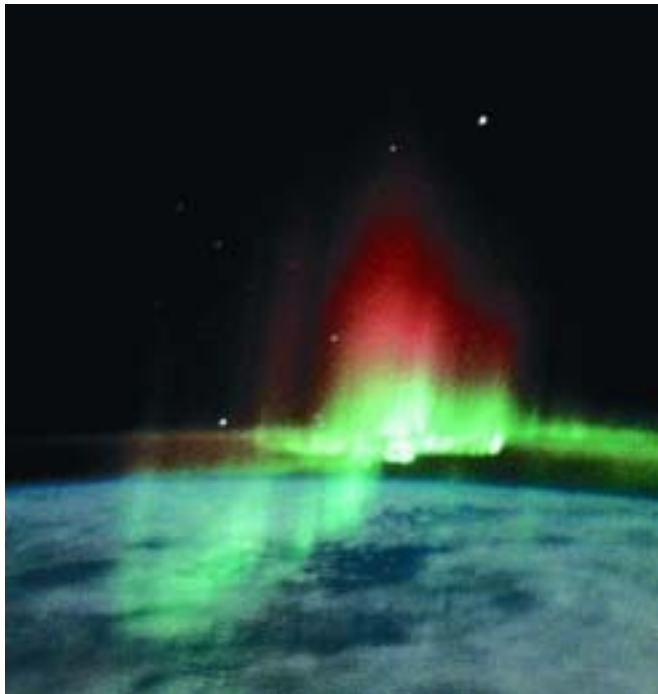
Mao and Bell's achievements with the diamond-anvil cell immediately prompted high-pressure scientists to test Wigner's prediction and search for the metallic state of hydrogen. Unfortunately, a quarter-century later, and nearly 70 years after Wigner's proposal, no research group has been able to show conclusively that they have managed to turn hydrogen into a metallic solid under static compression in the laboratory, despite tremendous effort.

It turns out that Wigner's proposal, though probably correct at much high-

er pressure, was not entirely correct in detailing how and when metallization takes place. The emerging explanation lies in a subtle interplay between chemistry and physics.

In the periodic table of the elements, hydrogen is traditionally placed in the upper left corner, right above lithium and sodium. Column I of the table is where Dmitri Mendeleev, its originator, placed the alkali atoms—atoms with a single valence electron. The atomic state of hydrogen certainly meets this criterion. However, adding an electron to a hydrogen atom creates a rather stable ion, a criterion Mendeleev used to place atoms such as iodine on the opposite side of the periodic table in Column XVII.

Wigner's proposal relied heavily on this chemical ambiguity. At low density, the diatomic state of hydrogen ( $H_2$ ), in which each hydrogen atom exhibits the behavior of a Column XVII element, is clearly preferred. But at sufficiently high compression hydrogen jumps across the table to Column I, where Mendeleev placed it. Unfortunately, a careful determination of the pressure at which this transition happens requires solving the quantum mechanics of the electrons and comparing their energy in the two states—the insulating diatomic state and the metallic monoatomic state. The basic equations of quantum mechanics had just been laid out in 1935 and already solved ex-



**Figure 4.** Planetary aurorae, the light displays produced by collisions between charged electrons in the solar wind and the atmosphere, illuminate the lines of magnetic force generated by planetary cores. Earth has aurorae near the South and North Poles; the latter, the aurora borealis, is seen at left in a Space Shuttle image. Jupiter's aurorae, one of which is shown in the Hubble Space Telescope image above, are more elaborate, revealing the stronger and more powerful magnetosphere surrounding Jupiter. The magnetosphere is part of the evidence indicating that much of Jupiter's interior must consist of hydrogen in a fluid metallic state. (Space Shuttle image courtesy of NASA; Hubble Space Telescope image courtesy of NASA/ESA and John Clarke.)

actly for a number of extremely simple cases, including the hydrogen atom itself. But solving such equations for a more complex case such as high-pressure solid, metallic hydrogen required huge approximations. Wigner ended up greatly underestimating the transition pressure.

Today, refinements in theory and extrapolations from experiments yield estimates indicating that hydrogen metallizes at pressures exceeding 4 million atmospheres—barely within the range of diamond-anvil cells. Moreover, it is currently believed that hydrogen metallization may be a matter more complex than a simple jump across the periodic table. Recent experiments have shown that iodine turns metallic while in the diatomic state ( $I_2$ ) and becomes a monatomic alkali-like solid only at higher pressures. In other words, the route to metallic hydrogen might not be straightforward but may involve a sequence of transitions yet to be uncovered.

### A Shocking Solution

The fact that hydrogen is reluctant to metallize on compression raised questions about our view of Jupiter. Is metallic hydrogen not so ubiquitous in Jupiter after all, but rather found limited to those areas close to the planetary core where the pressure is highest?

A close look at Figure 5 suggests a possible answer. The interiors of giant planets are in fact subjected to extreme

pressures and extreme temperatures at the same time. Perhaps, theorists conjectured, temperature could play an unexpected role in metallization. Unfortunately this was a conjecture that could not be tested by studies using diamond-anvil cells. Heating materials inside a diamond-anvil cell is difficult, particularly in the case of hydrogen. Hot hydrogen tends to react with the gasket that holds it between the anvil tips as well as with the diamonds themselves. As a result, the highest temperature that has been reached in a diamond cell containing hydrogen is still below 850 kelvins—although, as we note below, important studies of combined pressure-temperature effects in other elements have been accomplished with diamond cells. (A kelvin, a degree on the Kelvin temperature scale, is equal to a centigrade degree, but the scale begins at absolute zero, or  $-273.15$  degrees Celsius.)

Compressing hydrogen with shock waves seemed a more promising approach to the temperature question. Indeed, shock-wave experiments suffer from the opposite problem. Pressures in the million-atmosphere range can only be reached with an intense shock wave, of the sort generated when a metal projectile or an extremely intense pulse of laser light smashes into a sample. But the more intense the shock, the higher the final temperature of the sample. When directly shocked to a million atmospheres, hydrogen heats up to tem-

peratures in excess of 20,000 kelvins, far above the range of temperatures estimated for the corresponding depths of the planetary interior.

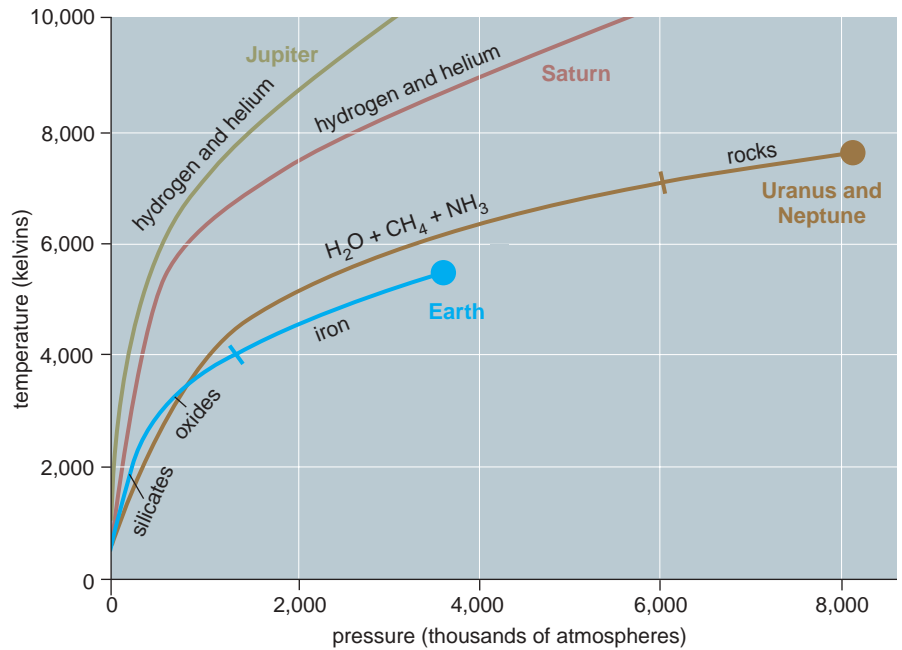
But in 1995, Bill Nellis, Sam Weir, Arthur Mitchell and their coworkers at Lawrence Livermore National Laboratory managed to design and operate a shock-wave apparatus that was improved with a couple of old tricks of the trade. First they cooled down the pre-shocked sample so as to increase its density and bring it closer to the target value. Second, they designed the apparatus in such a way that the shock wave would reverberate between the projectile and the chamber walls.

Calculations predicted that much higher pressures could be reached with a reverberating shock, and without so large a temperature increase. At variance with diamond-anvil experiments, where the sample can be kept in a compressed state for an unlimited time, measurements in a shock-wave experiment must be carried out rather quickly. In less than one microsecond the whole sample assembly blows up, incinerated by the blast. But Nellis's team finally managed to measure the electrical conductivity of hydrogen up to 1.8 million atmospheres and 2,900 kelvins, very close to jovian-core temperature and pressure conditions, and found that hydrogen turns metallic at 1.4 million atmospheres and 2,600 kelvins, less than half the pressure

plausibly required to metallize it at room temperature. Neither Wigner nor the diamond-cell scientists engaged in the search for metallic hydrogen could have anticipated that the effect of high temperature would be so dramatic. But the final picture of Jupiter that emerged from the shock experiments was quite neat. The measured conductivity and the new estimate of the transition pressure to metallization were consistent with the strength and pattern of Jupiter's surface magnetic field. Every brick of the model was now falling into its proper place, from the microscopic scale of the shock-wave experiment, to the planetary scale of the magnetic field generation.

### Diamonds in the Sky

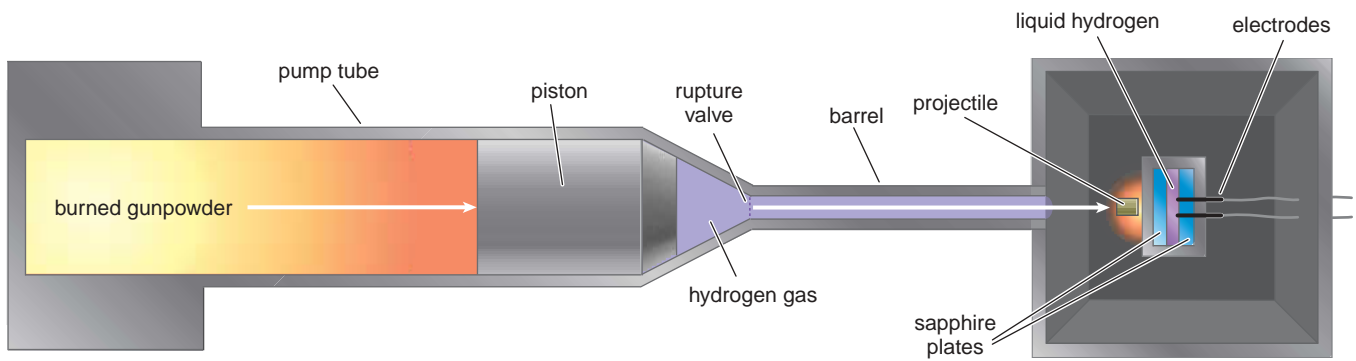
Neptune and Uranus lie near the borders of the solar system, a few billion kilometers from the Sun. It is not surprising, then, that the first serious attempts to model the interiors of these planets began only on the occasion of the Voyager II fly-by, less than 20 years ago. Yet, based on their density and distance from the Sun, scientists have long speculated that the interiors of Neptune and Uranus must be compositionally more rich than those of Jupiter and Saturn—with water, ammonia and methane, the so-called planetary ices, contributing about 80 percent of the mass of each planet. Indeed, spectroscopic studies conclusively reveal the presence of these molecules in the outer atmospheres of these planets, as well as in the atmospheres of small stars known as “brown dwarfs.”



**Figure 5.** Experiments have begun to shed light on how temperature and pressure may interact to create unusual states of matter in planetary interiors. In the gas giants, temperature is thought to play a significant role. Shock-wave experiments suggest that high temperature causes hydrogen to metallize at a fraction of the pressure required to cause this transition at room temperature, supporting predictions that much of Jupiter may consist of metallic hydrogen. Temperatures are not believed to reach similar heights in the interiors of Uranus and Neptune, which can be more closely modeled with diamond-anvil experiments and computer simulations. Likewise the pressure and temperature conditions at the center of Earth are within range of diamond-anvil experiments incorporating laser heating of iron, but technical issues prompt continuing debate about interpretation of the experimental results.

To be fair, little was known about the actual state of these molecular ices at deep-planetary conditions before scientists started to reproduce Neptune's pressures and temperatures in the laboratory. So it was startling news indeed when Marvin Ross, analyzing fresh shock-wave data on methane taken by his colleagues at Livermore, announced

in 1981 that a giant mine of diamonds could hide in the core of Neptune. Methane is composed of one carbon and four hydrogen atoms ( $\text{CH}_4$ ), but extreme compression, Ross argued, was causing the molecule to completely dissociate, and its carbon atoms would re-aggregate into their most stable form at those conditions—diamond. Al-



**Figure 6.** Shock-wave experiments compress matter to high pressures and high temperatures, using a laser light pulse or projectile to smash a sample. In the mid-1990s, a team at Lawrence Livermore National Laboratory built an apparatus capable of shocking a hydrogen sample to a pressure of 1.8 million atmospheres and a temperature of 2,900 kelvins, close to the conditions in the jovian core. Their experiments showed that high temperature dramatically reduced the pressure needed to cause hydrogen to metallize, yielding support for the notion that much of Jupiter's interior consists of metallic hydrogen. In the shock-wave “gun,” a liquid-hydrogen sample is cooled and placed in a holder. Hot gases from a gunpowder explosion propel a piston that compresses hydrogen gas in a piston tube; the gas rushes into the barrel of the gun to propel a projectile toward the sample. The intense shock of the impact subjects the sample, for an instant, to planetary-interior conditions.

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though there was no doubt that this had to be the fate of methane in the deepest regions of Neptune, the question remained as to whether methane had to be completely erased from the list of components of the planetary interior. A hint of the answer to this question came only in 1996, but it came neither from shock waves nor from diamond-anvil experiments. In fact it came not from experiment but from a radically different way of simulating planetary interiors.

Extracting information about the large-scale composition of a planet from a shock lasting less than a millionth of a second or from a squeezed sample weighing a millionth of a gram was a giant leap for planetary science and a fascinating example of scientific endeavor. But because the laws of nature must hold down to the atomic scale, there is no reason why such an experiment cannot be miniaturized even further, to the point that the sample consists of just a few molecules. This is the scale where available theoretical methodologies and current computing facilities allow physicists and chemists to solve the basic equations that govern the behavior of electrons

and atoms in matter and provide a detailed picture of how atoms bounce into one another, vibrate and get squeezed under the combined action of pressure and temperature.

The idea of simulating the behavior of matter at the atomic scale is actually as old as the computer itself. Enrico Fermi, Stanislaw Ulam and John Pasta were probably the first to recognize, in 1955, the potential benefit of using computers to solve Newton's equations of motion. They solved the real-time dynamics of a collection of interacting point masses coupled with springs—a highly idealized system indeed. But methodological developments, theoretical advances in our understanding of how atoms interact (through quantum mechanics) and, not least, breathtaking increases in the speed of computers have brought us to a point where the idea of simulating a bunch of atoms from the bottom up—by solving exactly the laws of quantum and classical mechanics—has become as feasible as squeezing the real material in a diamond-anvil cell or in a shock-wave apparatus.

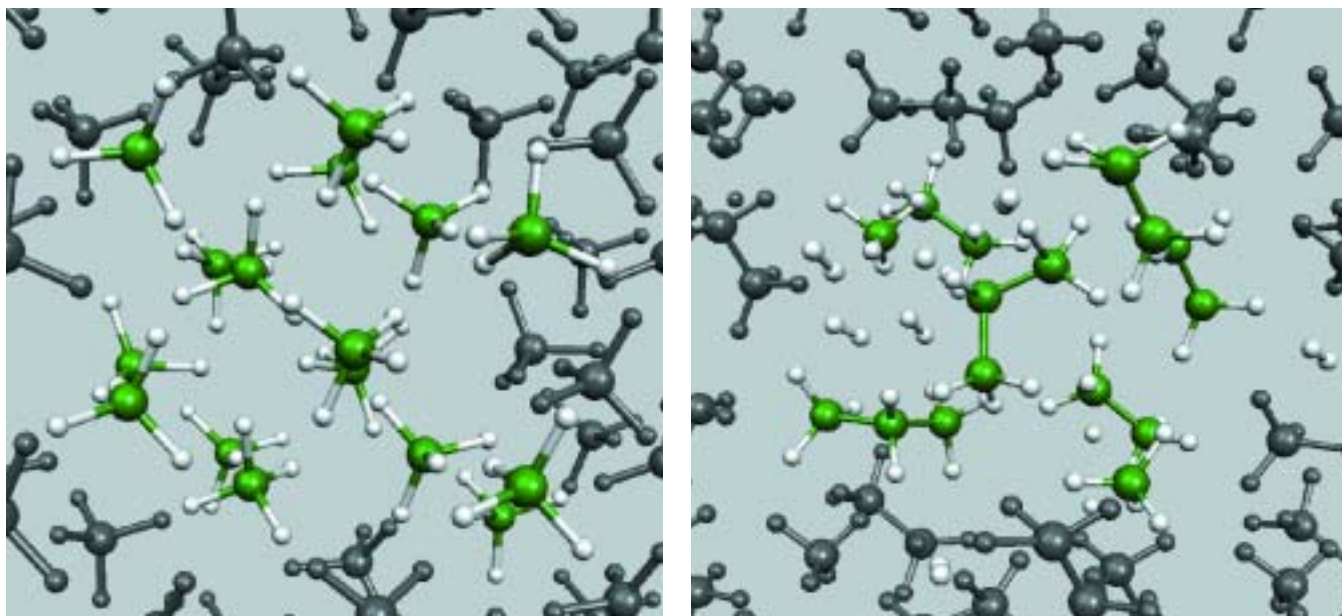
So it was that in 1996, one of us (Scandolo), with colleagues in Trieste,

Italy, set about to simulate on the computer the fate of methane at the conditions of pressure and temperature of the interior of Neptune.

### Virtual Neptune

In concept, a simulation of the behavior of methane at planetary conditions does not differ tremendously from what Fermi, Pasta and Ulam had done four decades earlier. The Trieste group took a bunch of molecules—16 was the maximum number we could afford with the supercomputers available at the time—put them in a simulation cell and let the positions of the atoms evolve according to Newton's equations—that is, with an acceleration equal to the force divided by the atomic mass.

Newton's equations are solved in this case by dividing time into very short intervals, each less than a femtosecond ( $10^{-15}$  second) long, calculating forces at every time step and updating the atomic positions accordingly. One picosecond ( $10^{-12}$  second) of dynamics requires repeating this operation more than a thousand times. We needed a supercomputer instead of the rudimentary punch-card machines available to our 1950s predecessors because the force ex-



**Figure 7.** Could the center of Neptune be filled with diamonds? Shock-wave experiments with methane, which has the chemical formula  $\text{CH}_4$ , suggested that extreme pressures could cause methane to dissociate—separating its carbon and hydrogen atoms. Under such conditions the carbon atoms would be expected to aggregate to form diamond, carbon's most stable form. Support for this prediction came from computer simulations. Author Scandolo and colleagues at the Abdus Salam International Centre for Theoretical Physics in Trieste, Italy, simulated the dynamics of 16 methane molecules and found that diamonds indeed formed at the high pressure–high temperature conditions of Neptune. At intermediate pressures, however, methane dissociated partially and formed hydrocarbon chains. Snapshots of this simulation are shown above. At left the original 16 methane molecules (one green carbon atom seen attached to four white hydrogens) are seen at conditions of relatively low temperature and pressure. After one picosecond at 4,000 kelvins temperature and 100 gigapascals pressure (about 1 million atmospheres), the molecules have dissociated and recombined, forming two methane, four ethane ( $\text{C}_2\text{H}_6$ ) and two propane ( $\text{C}_3\text{H}_8$ ) molecules, with extra hydrogens left mainly as diatomic molecules. (Reprinted from Ancilotto *et al.* 1997, by permission of the American Association for the Advancement of Science.)

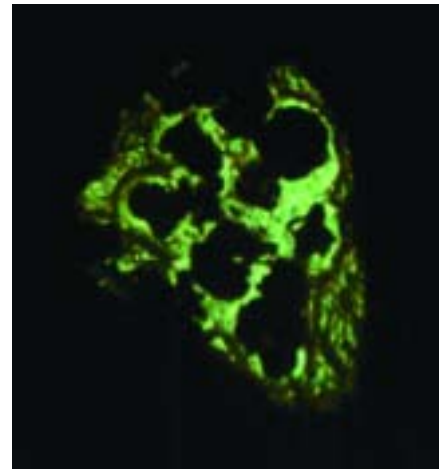
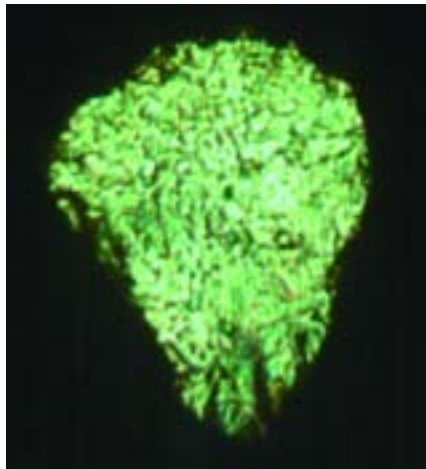
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erted by one atom on another atom cannot simply be modeled by a spring, as Fermi, Pasta and Ulam had postulated. Interactions between atoms are mediated by the presence of their electronic clouds. Electrons rearrange instantaneously with every change in the positions of the atoms and, depending on the external conditions applied to the system, can either hold atoms together as a kind of glue (a chemical bond) or cause their separation, as in the case of molecular dissociation.

Following the rearrangements of the electronic clouds, and thus calculating the forces acting on atoms, is an extremely difficult task that involves solving the quantum mechanics of hundreds of electrons simultaneously and repeating the operation as many times as the atomic dynamics require. It was no surprise, then, that two weeks of supercomputer time were needed to simulate just five picoseconds of the “real” dynamics of 16 methane molecules. Fortunately, chemical reactions such as dissociation take place very rapidly, typically on the femtosecond timescale, so we would not miss them if they happened in our simulated environment.

Mining this small virtual world, we found Ross’s diamonds. The results of the simulations confirmed Ross’s proposal that diamonds form under the conditions found in the deepest regions of Neptune. But the calculations unexpectedly yielded a different picture at intermediate pressures, those corresponding to the bulk of the planet. Instead of breaking down completely into its atomic constituents, methane in the simulation dissociated only partially and ended up forming hydrocarbon chains, chains of two to three carbon atoms surrounded by hydrogen atoms. The discovery added strength to Ross’s idea that methane had to be eliminated from the list of “ices,” and it implied that Neptune’s deep chemistry had to be more complex than previously thought. In particular, the production of hydrocarbons in the planetary interiors could account for the observed anomalous abundance of some of these substances in the atmosphere of the planet, where they might be brought up from the deep interior by convective currents.

Direct experimental confirmation of both hydrocarbon and diamond formation from methane at planetary conditions came only three years later, in 1999, from a diamond-anvil experiment



**Figure 8.** Experimental confirmation that hydrocarbons and diamonds could both form from methane at planetary conditions came from a diamond-anvil experiment carried out at the University of California, Berkeley, by author Jeanloz and coworkers. A methane sample is shown here in photomicrographs taken before (*left*) and after squeezing and laser heating in the diamond cell. In measurements of the infrared absorption spectra taken afterward, the signature of methane had faded, replaced by absorbance bands characteristic of doubly and triply bonded carbon in hydrocarbons. At the center of the laser beam, where heating was most intense, there was evidence of diamonds. (Image from Benedetti *et al.* 1999, reprinted by permission of the American Association for the Advancement of Science.)

carried out in Berkeley, California, by one of us (Jeanloz), with Robin Benedetti and other coworkers. Real diamonds popped out, floating in a bath of fluid hydrocarbons, when a methane sample was heated above 2,500 kelvins and compressed above 200,000 atmospheres in the diamond cell.

This figure was even lower than the required pressure for methane dissociation predicted by the computer simulations, which implies that perhaps no methane at all can be found deep inside Neptune. The findings have additional implications. The separation of methane into rising hydrogen and sinking diamond likely releases gravitational energy to drive the convective motions of the planet’s fluid interior. The amount of this energy appears to be large, comparable to the excess heat—over and above the heat received from the Sun—that infrared emissions indicate is released from Neptune’s interior.

### Earth’s Hottest Dispute

Our virtual journey to planetary interiors finally brings us home to Earth, the spaceship on which we reside. Although Earth is the most studied of all planets, its interior is still profoundly mysterious. It is also remarkably inaccessible. Yet the interior holds key information about how our planet formed and evolved over geological time, motivating decades of high-pressure experiments.

One of the most immediate questions is: How hot is the deep interior? It is the heat of the Earth’s mantle and core that causes geological activity, from volcanic eruptions and the movement of continents to earthquakes and the deposit of ore bodies. Much of that heat is left over from the formation of our planet, 4.5 billion years ago; additional heat comes from the decay of naturally occurring radioactive isotopes of elements such as potassium, thorium and uranium. It continues to drive the geological evolution of our spaceship.

The most direct way to answer this question is to determine the melting temperature of the material in the Earth’s core at high pressures. Measurements of seismic waves passing through the interior show that the outer core is liquid (with a viscosity thought to be comparable to that of the oceans), whereas the increase in pressure with depth causes the inner core to be solidified. Therefore, the interface between the inner and outer core must be at the freezing (or, if you prefer, melting) temperature of the core material at that depth. Because of the fluid nature of the deep interior, seismological measurements and the equations of fluid mechanics can be used to calculate the pressure at this boundary: 3.25 million atmospheres.

If we think of Earth as a huge press capable of showing us (were we able to



insert a thermometer) the freezing temperature of the core alloy at high pressures, we can imagine building a miniature version of this press in the laboratory to measure the melting and freezing temperatures of appropriate alloys at pressures in the range of 3 million to 4 million atmospheres. Were this possible, we could determine the temperature at the inner core–outer core boundary and, by a modest extrapolation, right to the center of the planet.

Michael Brown, then a graduate student at the University of Minnesota, started going to Los Alamos National Laboratory in the late 1970s to work with Robert McQueen, a leader in shock-wave experiments. Using methods that had been pioneered at the laboratory, Brown and McQueen showed that iron melts when shock-compressed to pressures of about 2.5 million atmospheres. They discovered that although the speed of sound in iron increases as the sample is shocked to higher pressures, the sound velocity drops at 2.5

million atmospheres in exactly the manner that would be expected for melting, thereafter increasing as the (molten) iron is shocked to higher pressures.

Published in 1982, these findings nicely paralleled those of Danish seismologist Inge Lehman, who discovered the inner core in 1936 by determining that the velocity of seismic waves abruptly increases at a depth that we now identify as the interface between the solid and liquid regions of the core.

Unfortunately, temperature could not be readily measured in the shock experiments at Los Alamos. Still, the discovery of the melting transition at high pressures was a major advance that motivated other investigators. Happily, unlike hydrogen, iron can be heated in a diamond-anvil cell using a laser beam. Within a few years, Quentin Williams and one of us (Jeanloz) were measuring the temperature of laser-heated iron at high pressures at the University of California, Berkeley. By measuring the spectrum of the

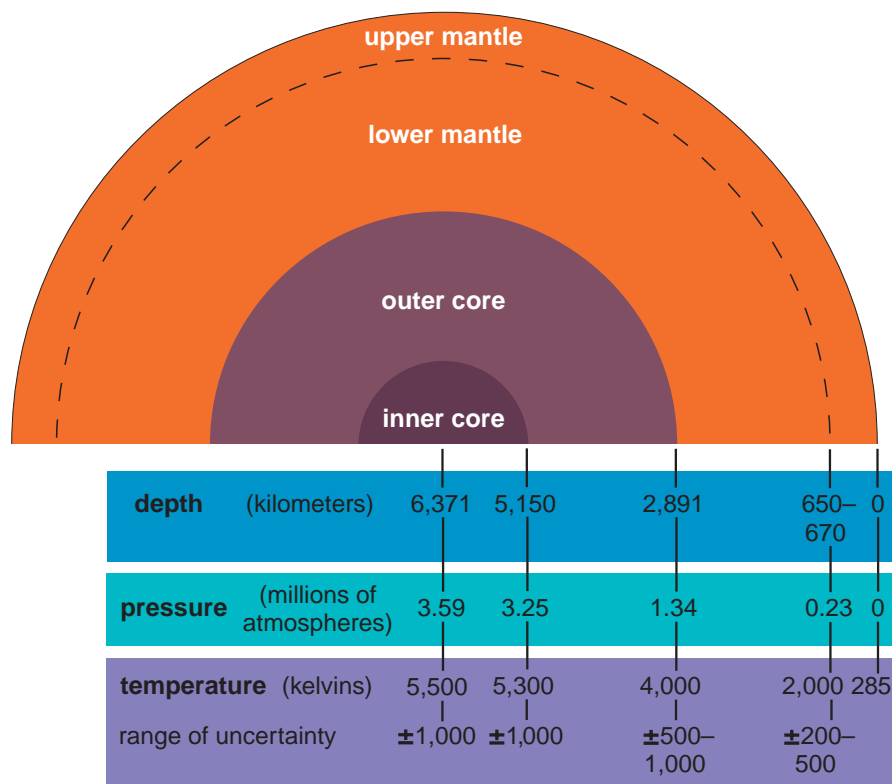
light emitted from the hot sample, we could gauge temperature by the same methods astronomers use to determine the surface temperatures of stars. The results were surprising: Instead of melting at about 3,000 kelvins, as expected, it seemed that iron required temperatures closer to 4,000 kelvins in order to melt at 1 million atmospheres of pressure.

At the same time, Thomas Ahrens, Jay Bass and their associates at Caltech had managed to use the same method as the Berkeley group to measure the temperature of iron as it is shock-compressed to 3 million atmospheres. They again found a surprisingly high temperature at the shock-melting point of 2.5 million atmospheres, about 6,500 kelvins, in good accord with the laser-heated diamond-cell experiments.

But there were problems. First, a laser cannot uniformly heat a sample inside a diamond cell. Only the center of the hot spot at the focus of the laser beam reaches peak temperatures, and the temperature drops off to room temperature within less than 0.1 millimeter from the center. Typically the emitted light varies from “white-hot” at the center to “red-hot” and then dark (no visible emission) within a short distance across the sample. An experimenter trying to measure the spectrum from a small sample squeezed at high pressure between relatively thick diamonds faces a tough technical challenge. In addition, the most interesting part of the sample is at high temperatures. The sample glows so brightly that it becomes difficult to be sure whether or not it has melted.

Similarly, there were technical problems interpreting shock-wave results, because the hot iron sample has to be contained long enough at high pressures to be able to reliably determine the temperature. A window has to be put on the back side of the sample, altering both the pressure and temperature achieved during the shock loading. Moreover, the experiment is over so quickly that even a sample at the melting temperature may not have time to melt; to achieve melting the experimenter might need to overshoot the true melting temperature, thus obtaining reproducible measurements that are consistently too high.

The agreement between static and dynamic experiments suggested that these difficulties had been overcome. However, the surprisingly high temperatures motivated others to try re-



**Figure 9.** Debate continues over exactly what temperatures prevail at the boundary between Earth’s liquid outer core and solid inner core. The pressures at boundaries between Earth’s interior layers are known from seismological and other evidence, but attempts to simulate temperatures in the core have produced varying results. General agreement is emerging that the Earth’s center may be as hot as the surface of the Sun—in the range of 5,000 to 6,000 kelvins. Here are shown temperature estimates derived from recent high-pressure experiments. More precise estimates of the temperature at the inner core–outer core boundary likely will require better modeling of the origin and evolution of the deep interior, which could reveal the role of alloying elements that could alter the melting point of iron.

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producing the results. Problems quickly arose, and during the 1990s groups in Germany, Sweden and the U.S. reported a variety of melting temperatures as they varied experimental parameters. Controversy arose as there were indications for and then against (and corresponding claims in the scientific literature) a new crystalline form of iron having been discovered at high pressures. In order to make sense of this large and confusing array of new data, the various groups have been refining their methods and applying ever more sophisticated tools.

Our picture of the inner core–outer core boundary will no doubt evolve as different methods are used to check these findings, and as refinements in laboratory techniques result in smaller experimental uncertainties. Good calibration standards have yet to be developed for measuring temperatures (let alone melting temperatures) in the 3,000- to 5,000-kelvin range. But this also leaves us with the question: How good is “good enough”?

We may be nearly there. The fact is that the Earth’s core is not pure iron but contains about 10 percent (by weight) of other constituents. If you compare the density of the outer core that is derived from seismological data with that of pure iron shocked to comparable pressures and temperatures, the core’s density turns out to be about 10 percent lower. Even when the melting temperature of pure iron is accurately known at 2 million to 4 million atmospheres of pressure, we will still have to make a correction for the effect of contaminants. Alloying often decreases the freezing temperature of a material; this is why ice can be melted by putting salt on top of it. The actual freezing temperature at the inner–outer core boundary may therefore be 1,000 kelvins or so lower than that of pure iron.

Yet the exact makeup of the core alloy is impossible to know. The current composition of the core is the result of the processes by which it first formed and subsequently evolved over geological time. There are many competing ideas: Carbon and sulfur, oxygen and even hydrogen have been proposed as candidates for the primary alloying component. High-pressure melting studies of such alloys are ongoing. It is already clear that the addition of hydrogen or sulfur may significantly lower the melting temperature of iron, but this is not the case for other

alloying components. A good model for the origin and evolution of the Earth’s deep interior will be required before we can determine the compositions relevant for experimental study and ultimately make a good estimate of the temperature at depth.

The current uncertainty over the core’s composition thus parallels the uncertainty resulting from the various experimental results, which, although somewhat scattered, are in general agreement. An interplay between the two—where a refined understanding of the evolution and composition of the core drives new experiments to determine the behavior of alloys at high pressures—seems most likely to answer large questions about the center of Earth.

### (Still) Having a Heat Wave

Broadly speaking, however, these experiments have truly rewritten the texts about the Earth’s interior. Before the shock-wave and diamond-cell experiments, estimates of core temperatures were little more than educated guesses. From values of 3,500 to 4,300 kelvins, estimates of the central temperature have nearly doubled to 5,500–6,000 kelvins. To be sure, the uncertainty on this estimate is as big as ever—about 1,000 kelvins in either direction—but the effects of alloying and experimental uncertainties are being factored into estimates that are now based on measurement.

It turns out that the temperature at the center of our planet is likely to be comparable to that of the glowing-hot surface of the Sun. How did our planet get so hot in the first place? How has it managed to retain so much heat? Our rocky planet’s mantle overturns itself over geological time, like a thick gravy heating in a pan on the stove. But the flame is on low—it is thought that there is only relatively modest heating from natural radioactivity at great depth—so how can it be that our planet has not cooled itself off by now, and that it remains so geologically vigorous? The greatest surprises may lie not within the mysterious planets in the sky, but within the roiling, boiling one beneath our feet.

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