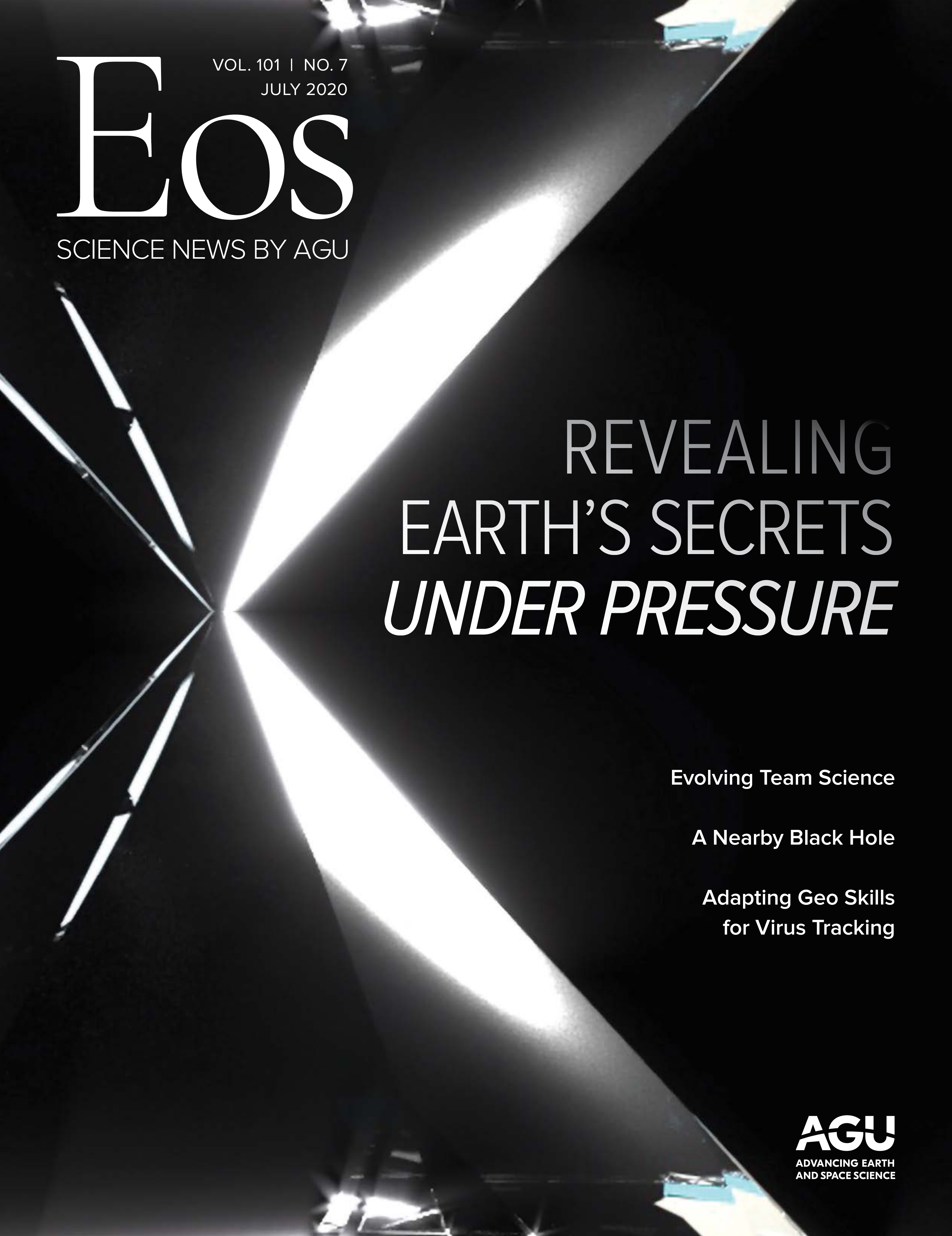

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Remaking a Planet One Atom at a Time

BY KIMBERLY M. S. CARTIER

When is a planet not a planet? Where does helium rain? How can water be solid and liquid at the same time? For answers, scientists put common planetary materials under extreme pressure and watched what happened next.

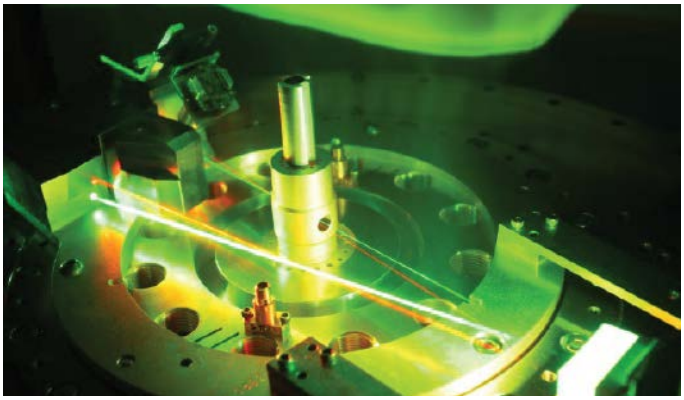
Sandia National Laboratories' Saturn accelerator (above) and its more powerful Z machine are pulsed power machines. They deliver high-power X-ray pulses to drive test samples to extreme temperatures and pressures. Credit: Randy Montoya, Sandia National Laboratories

In one of the most technologically advanced laboratories ever built, a high-energy laser powers up. It fires a pulse of light that lasts just fractions of a second, striking minuscule samples of the most common materials in the universe.

The shock wave might create never-before-seen types of matter that exist in the hearts of planets. Or it might create minerals that lay strewn across the cratered surfaces of moons and speckled through asteroids and meteorites, dutifully keeping a record of their chaotic past.

It sounds like science fiction—and, in fact, has been portrayed as such on the big screen (see image on p. 33). But these experiments are science reality and take place at not one but many high-energy laboratories around the globe. The technique is one example of dynamic compression, named for its speed and the intense pressure created. Rapidly squeezing planetary materials replicates the processes that take place in the interiors of planets and during energetic events like collisions and impacts.

"We started thinking about how to really synthesize the conditions of planetary interiors in the laboratory," said Arianna Gleason, an experimental mineral physicist at SLAC National Accelerator Laboratory and Stanford University in Menlo Park, Calif.



Lasers help align the hardware and diagnostic tools before the Z machine is fired. During compression, X-ray lasers are often used to take data. Credit: Sandia National Laboratories

We're "taking the minerals that we're used to seeing every day—quartz, feldspar, stuff that humans have constant contact with—and asking the question, What do they look like, and what are their properties at extreme conditions?"

Hydrogen, helium, methane, water, silicates, iron—all of these common planetary materials can change between solid, liquid, and gas inside or on the surface of a planet depending on the pressure and temperature. These atomic-scale changes can determine whether the planet has a core and a mantle, whether it has a magnetic field, whether it survives a catastrophic impact, and whether it can support life.

For more than half a century, dynamic compression experiments have allowed scientists to see what happens to ordinary planetary material at the center of the Earth. The inner workings of larger planets and exoplanets have only recently been accessible from the lab.

> **We're "taking the minerals that we're used to seeing every day...and asking the question, What do they look like, and what are their properties at extreme conditions?"**

Diamonds, Guns, and Lasers

Before all of the moving parts of dynamic pressure experiments came the steady pressure of static experiments, in which scientists "synthesize these high-pressure and -temperature conditions, but...hold them at those conditions over a long period of time—minutes, hours, even years," Gleason said.

The most common tool for this is called a diamond anvil cell, which squeezes samples literally between a rock and a hard place. "One's been in my drawer for years," said Gleason. Once a sample is under pressure, the scientists can check for any changes to its chemistry, molecular or crystal structure, visual properties, and phase.

"The community has been working at pressures at the order of a hundred gigapascals, 1 million atmospheres, for something approaching 50 years," said Raymond Jeanloz, a planetary scientist at the University of California, Berkeley. (The pressure at Earth's surface is 1 atmosphere.) "A hundred gigapascals is an important pressure for our field because that roughly corresponds to...the core-mantle boundary of the Earth." The center of Earth's core is about 3 times that pressure, which is well within reach of the newer, smaller diamond anvil cell designs that focus the same amount of force on a smaller sample size to generate larger pressures.

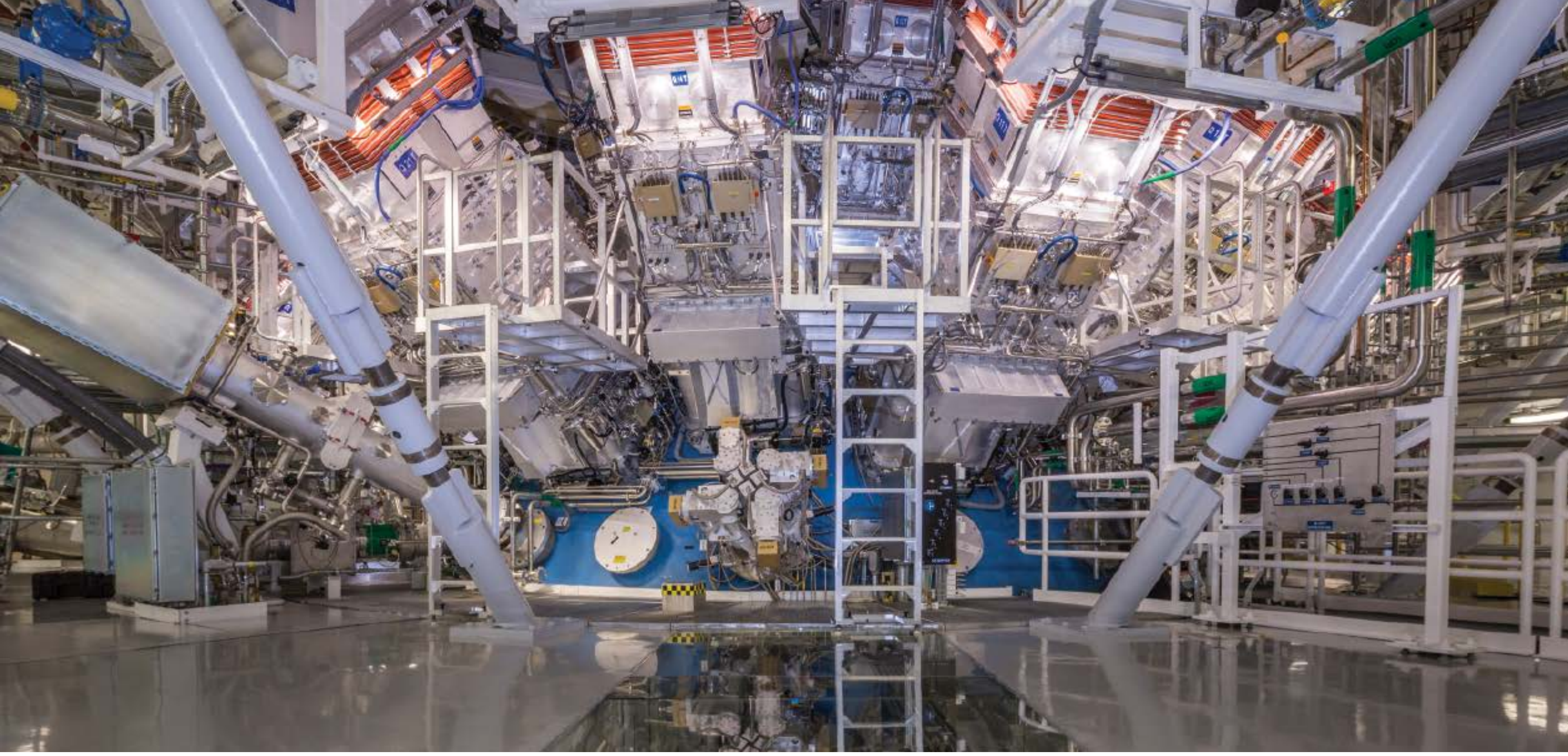
"Static compression definitely lays the groundwork and is the bedrock of the compression community in mineral physics," Gleason said. But diamonds are only so strong, and test samples can get only so small. Dynamic compression can reach the higher pressures found within ice giant, super-Earth, and gas giant planets and allows us to study events like impacts, in which change occurs rapidly. "We're talking about a really accelerated way of applying pressure."

"Back in the beginning of the field," said June Wicks, "there would be big gas guns located in basements of academic institutions, and that [technique] was the foundation of measuring equations of state." Projectiles fired at very high speeds strike a target sample within a test chamber, and then scientists can watch pressure waves propagate through the target and study the changes.

Wicks, a planetary scientist at Johns Hopkins University in Baltimore, Md., uses laser-driven compression experiments to study how atoms and molecules move and interact inside planets. In the past 20 or so years, Wicks said, compression using high-energy optical lasers, like the one at SLAC National Accelerator Laboratory, has advanced to the front of the field.

"You focus [the laser] on your sample, it turns the surface into a plasma, and that plasma expands and sends an equal and opposite pressure wave into your sample," Wicks said. All of this takes place in a few billionths of a second.

Using lasers and pulsed power sources, "people have studied materials to pressures as high as a billion atmospheres...a thousand-fold increase" over what's achievable with static compression, Jeanloz said. Shorter laser pulses achieve higher pressures as more power strikes the sample all at once.



Laser-driven compression can shock planetary materials into states of matter that exist only in the deep interiors of planets. Shown here is the target bay of the National Ignition Facility, one of the leading instruments for these experiments and also the set of the Starship Enterprise*'s warp core in* Star Trek: Into Darkness *(2013). Credit: Damien Jemison, Lawrence Livermore National Laboratory*

"It's as much power as is in a bolt of lightning in a split second," Gleason said.

Helium Rain Brightens Saturn

On Earth it rains liquid water, but on Saturn it rains liquid helium. We know this because experiments using the lasers at the National Ignition Facility at Lawrence Livermore National Laboratory in Livermore, Calif., have validated predictions of when hydrogen and helium mix together and when they separate, a property called miscibility.

"Hydrogen is the most populous element in the universe, and hydrogen is somehow involved in every planetary body" as itself or within compounds like water and methane, said Takuo Okuchi, an associate professor at Okayama University's Institute for Planetary Materials in Japan. "Its chemical state is very, very different depending on its environment, [in essence, its] pressure and temperature condition."

At the pressures found inside Jupiter and Saturn, Okuchi explained, hydrogen becomes metallic, meaning that hydrogen atoms are so tightly packed that their electrons overlap. Liquid metallic hydrogen sustains the magnetic field inside these gas giant planets. (Inside Uranus and Neptune, water becomes metallic, Okuchi said.)

"At high enough pressures and temperatures, hydrogen and helium dissolve into one another and they make a continuous fluid," said Sarah Stewart, a planetary scientist at the University of California, Davis. "They're not a gas anymore because they're at such high pressure, but we call it a fluid. But then there's a boundary where if you go below a certain temperature, helium will form droplets and then rain down into the interior."

"It's like oil and water," Jeanloz said.

Saturn is about 50% brighter than it should be based on its age, and Stewart explained that this might be because helium rains on Saturn but not on Jupiter. "This is an idea that's been around for a while, but only recently have we been able to get to those conditions in the lab."

"These atomic-level changes have planet-sized implications," said Wicks.

"At high enough pressures and temperatures, hydrogen and helium dissolve into one another and they make a continuous fluid."

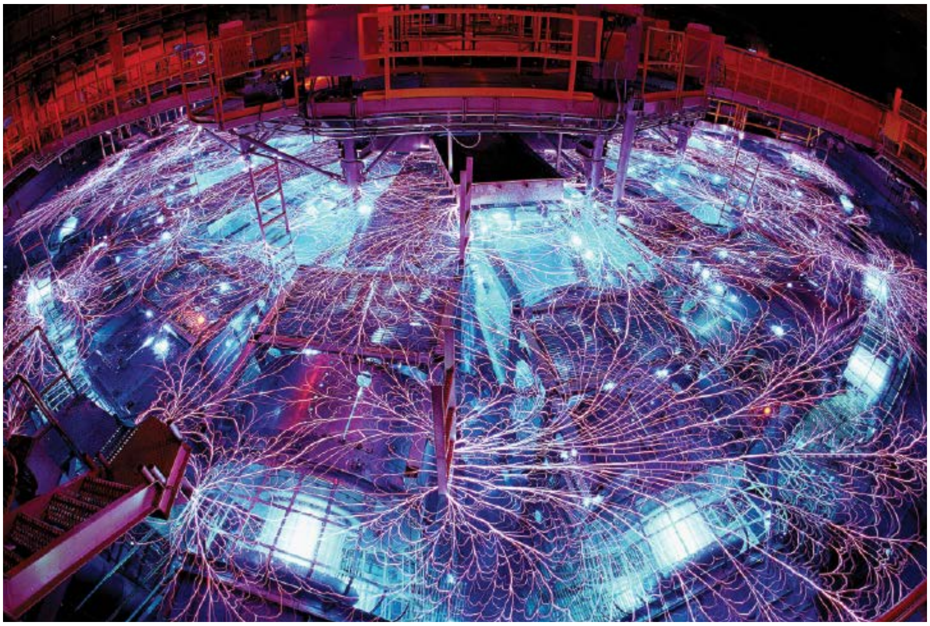
Diamonds Decorate Neptune's Sky

Ice giants like Uranus and Neptune have a higher fraction of methane (CH_4), water (H_2O), and ammonia (NH_3) than gas giants do, and dynamic compression experiments have shown that rain there gets even stranger. A team led by Dominik Kraus explored what happens to a pure hydrocarbon material when it's exposed to the conditions inside a planet where it might exist—in this case, Neptune.

"We have now seen the formation of nanodiamonds," said Kraus, an experimental physicist at Helmholtz Zentrum Dresden Rossendorf in Germany. The pressures of the nanosecond laser compression broke the molecular bonds holding hydrogen and carbon together and compressed the carbon into nanometer-scale diamonds. The discovery confirmed a long-held theory.

Experiments like this highlight an advantage that laser compression has over diamond anvil cells. Both types of experiments often use the brightest X-ray sources to analyze the microscopic structure of the samples before, during, and after compression. But when you're looking for the signatures of tiny diamonds, Kraus said, it's easier if the compression itself isn't done with diamonds.

Moreover, hydrogen "reacts with any surrounding material," Okuchi said, including the capsule that contains the laser target. So does water, another common planetary material. "By using a very strong laser beam, we immediately compress the material within nanoseconds" and make multiple measurements within that same time frame. "This is the best way to measure at such extreme conditions without any contamination, without any reaction."



The Z machine uses electrical currents and magnetic fields to generate high temperatures, high pressures, and high-powered X-rays. Scientists have used this instrument to understand the equations of state of common planetary materials. Credit: Randy Montoya/Sandia National Laboratories

Taking the results of nanosecond experiments and applying them to planetary timescales can be a “fuzzy” endeavor. “Certainly, something that happens in nanoseconds will also happen in millions of years,” Kraus said. “The question is, What else can happen that we cannot see in our small timescales?”

The ultrashort timescale, essential for driving planetary materials to planetary pressures, is also this method’s “biggest weakness,” according to Wicks. “We’re trying to ask questions about…the fate of the interior of a planet, which is on superlong timescales, with an experiment that’s 1 nanosecond.… The more extreme the states that we get to, the shorter the timescale you have to do it in.”

Solid–Liquid Water Complicates Ice Giants

A better understanding of the material processes inside Uranus and Neptune can also help us understand the most common type of exoplanet.

Among extrasolar planets, Kraus said, “there’s this big abundance of mini-Neptunes, which are probably the same as Uranus and Neptune, just without much of the hydrogen-helium atmosphere. So, really, a thick, icy mixture.”

Experiments published in 2018 revealed that “icy” is much more complicated for ice giants than previously thought. “We found this unusual superionic state for water that exists only at high pressures and temperatures that are similar to what we expect inside Neptune and Uranus,” said Marius Millot, a physicist at Lawrence Livermore National Laboratory. “Superionic ice is a new state of matter.”

Millot led the team of researchers who discovered this previously unknown state of matter. They used first a diamond anvil cell and then Rochester University’s Omega Laser Facility to force the water to crystallize into this new state.

“For water, [superionic ice] is a state where the oxygen atoms that form the H_2O molecule that we’re familiar with continue to form a solid lattice, like in ice that we know,” Millot said. “But unlike the ice we know and that is in our ice cubes, in superionic ice the hydrogen is actually free to move around within this lattice of oxygen. Basically, the hydrogen atoms are moving around almost like a fluid within the solid crystal made of the oxygen. It’s a very unusual solid–liquid state.”

“We’re trying to ask questions about…the fate of the interior of a planet, which is on superlong timescales, with an experiment that’s 1 nanosecond

At the pressure of an ice giant’s mantle (roughly 200 million atmospheres), superionic ice melts at temperatures near 4,700°C, much hotter than its environment. The team confirmed the ice’s novel crystal structure in later research. “It could be that this superionic ice actually doesn’t melt even inside Neptune and Uranus,” Millot said, and so the planets could be quite solid.

The flowing hydrogen atoms carry a charge with them, and so they interact with and possibly influence the planets’ magnetic fields. What’s more, the structure and energy transport within the planets can alter other observable phenomena like weather, according to Kraus.

The trouble in applying these new discoveries to our ice giants comes from the lack of observational data. Uranus and Neptune were each visited only briefly by Voyager 2 in the 1980s, and so we lack detailed knowledge of the planets’ gravities, magnetic fields, weathers, and compositions that could better unite experiments and theory.

Kraus explained that experimentalists are working with the teams designing a possible future ice giant mission. Compression experiments constrain what conditions a probe might encounter, identify what data mission scientists need to collect, and put observations into context.

Conducting high-pressure experiments “starting with our ice giants is already very difficult,” Kraus said. To then apply our knowledge to exoplanets, “you need to rely on those constraints that you already have for all our planets to think [of] what can also be possible.”

Earth Was Unmade and Made Again

Beyond improving our understanding of the current state inside planets, dynamic compression is also an invaluable tool for understanding sudden, transient high-energy events like impacts that can knock planetary evolution off course.

Consider the Earth and Moon. The chemical signatures of Earth rocks and Moon rocks suggest that a major impact long ago scraped material off Earth that then formed the Moon. But by combining high-pressure mineral physics and computer simulations, Stewart’s lab found that for some time after this impact, the Earth might have ceased to be a planet.

Instead, Earth was a synestia: a molten and fluid iron-rock blob, maybe shaped like a doughnut or flying saucer. “We’re used to thinking of the atmosphere being separate from the rock,” Stewart said, “meaning the gases that we’re breathing. Part of us trying to understand what happened after the giant impact was the miscibility of the outer parts of a synestia in our calculations. The iron, the rock, and the atmosphere are all dissolved into one another in a single fluid. They are all entirely miscible."

The synestia Earth was constantly changing its shape and sections rotated at different speeds, which violate the definition of a planet. "We were looking at the actual thermodynamic states and how they had changed and tried to understand what was produced by looking at the material properties," Stewart said. "That was what really opened the door for us to figure out that the planet could turn into something that was a new thing."

"Simulations are key to understanding impact phenomena, and we can't re-create all the conditions in the lab by doing impacts in the lab because we don't have the gravitational forces that you need in a real planetary event," Stewart said. "We gather basic material data about rocks and minerals," but simulations and ab initio modeling are essential to understanding what they mean for planetary evolution.

Many Planets Are Fuzzy Inside

Earth gained a Moon and became a planet once more, but learning the conditions under which iron and silicates mix together raised new questions about whether they fully separate into distinct layers within a planet. The textbook-standard planet model with defined layers of iron, silicate, and air is the bedrock of our theories of how planets transport heat and generate magnetic fields. However, experiments on iron-silicate alloys suggest that the boundaries might be much blurrier.

"Planets that are super-Earths could look like an Earth—iron core, rocky layer, and then just a thicker atmosphere—or they could look very different in that it's so hot on the inside that now iron and rock can dissolve into one another and there's not a clearly separated metal core," Stewart said.

"And then the same thing at the interface between what would have been the surface and the atmosphere," said Stewart. "The interior can reach high enough pressures and temperatures that that atmosphere-surface boundary becomes fuzzy as well, where part of the atmosphere dissolves into a magma [and] part of the magma actually dissolves into the atmosphere."

"Our conception of layered planets may be completely false. We haven't been able to measure this experimentally yet, but we will [be] in the next 10 years," Wicks said.

Impacts Record Solar System History

Roughly 4 billion years ago, the inner solar system was showered with bolides. Radioisotope dating of the minerals created by impacts can estimate when it happened, and shock features in grains can reveal how large an impact was. "The zircon age or baddeleyite age plays a very important role for us to constrain the whole history" of the bombardment, said Ai-Cheng Zhang, a professor of mineralogy at Nanjing University in China. "But for some of [the zircons], we don't know the exact meaning of the age" or precisely what it indicates.

Zhang studies the minerals that form through high-pressure impact events in samples of asteroids, Mars, and the Moon. "We want to understand why there are some differences between the impact records in different samples. Are they related to impact velocity? Or related to the heliocentric distance from the Sun? Currently, we don't know very well," Zhang said. "This information is critical for establishing a model to understand the dynamics in the solar system, especially the inner solar system."

Our understanding is limited by what we know of how minerals start their radioisotope clock and what processes can reset it. Zhang has analyzed meteorites and samples returned from missions trying to figure this out. "We are still working to decipher whether impact events affected the zircon or baddeleyite age, based on our mineralogical study and geochronology investigations," he said. This will tell us whether the era of impacts happened across the inner solar system all at once or in waves.

The effort to pin down the solar system's impact history "tackle[s] the question of habitability on the early Earth and other bodies," Stewart said. "You can point to [impacts] and say maybe that's why Earth and Mars and Venus are different, but we can't really explain how that happened."

The Expanding Field of Compression

As labs in the United States, Europe, and Asia have brought newer instruments online, the extreme pressures and temperatures that planetary materials endure have become more accessible to researchers around the world.

"Depending on the pressure range and the question that we're interested in," Wicks said, "we have a slew of techniques to get to high pressure, a slew of techniques to probe the states. And those techniques are getting better and better." The facilities might be dedicated mostly to other areas of high-energy physics like nuclear fusion and plasmas, "but we get to tag along with our rocks afterward and ask our questions."

Not only are newer instruments raising the upper limit on pressure, but also they can yield more data than before from each experiment, and more quickly, too. Whereas the first laser compression facilities could fire only a few times a day, now they can test samples every few minutes.

"Mineral physics is about to face a big data problem," Wicks said. "Not a problem, an opportunity."

> "Mineral physics is about to face a big data problem," Wicks said. "Not a problem, an opportunity."

Some teams are looking ahead to how machine learning can guide experiment design not just to find the best tools to answer a question but also to prioritize which questions to ask first.

For some experimentalists, the next steps aim to test more realistic mixtures of planetary materials. Ice giants, after all, aren't made of only water or only hydrocarbons. Others seek to constrain material properties like electrical conductivity, viscosity, and cooling rate, which connect with large-scale planetary features like brightness, weather, and magnetic fields. Still others want to glean new information from familiar materials by leveraging the unique properties of lasers, measuring the compressed samples more accurately, and using more advanced instruments to gather data.

But high-pressure experimentalists can't answer these questions alone. "We certainly can't gather enough data on different chemical compositions to be able to finish the problem with just lab data," Stewart said. "We absolutely need modeling. And then, better constraints come from what we're seeing from the observers."

"There's room for everybody to play."

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