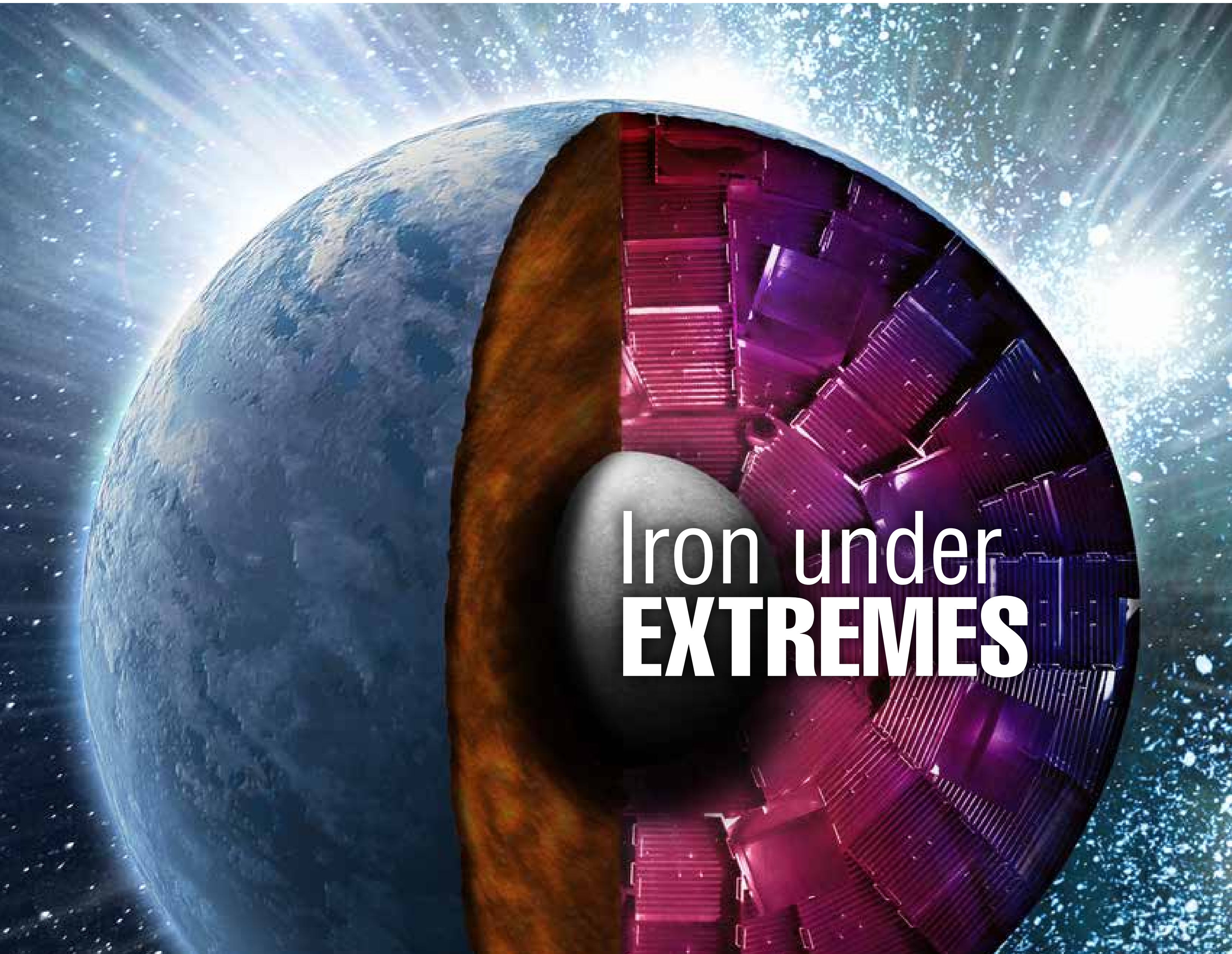


Iron under EXTREMES

THE rotation and convection of liquid iron within the Earth's core generates the magnetosphere, an expansive magnetic field that stretches across 12 million kilometers and protects us from harmful solar winds and cosmic radiation, allowing life to flourish. Many super-Earths—planets outside our solar system more massive than Earth, yet lighter than ice giants like Neptune and Uranus and made of gas, rock, or a combination of both—could also contain dynamos that generate their own magnetospheres. The lifetime of a dynamo depends on how and when its molten core crystallizes. By understanding the melting and solidification curve of iron under extreme conditions, scientists can characterize the potential for these exoplanets to have a sustained dynamo-generated magnetosphere that could support life.

Lawrence Livermore scientists have performed a series of experiments through the National Ignition Facility's (NIF's) Discovery Science Program to replicate the extreme conditions within super-Earth cores and answered many questions posited by theoretical predictions and extrapolations from previously established relatively low pressure–temperature experimental data. This series of 12 experiments at NIF have also opened new pathways for future research that will increase our understanding of the properties and performance of materials under extreme temperatures and pressures that contribute to the Laboratory's stockpile stewardship mission.

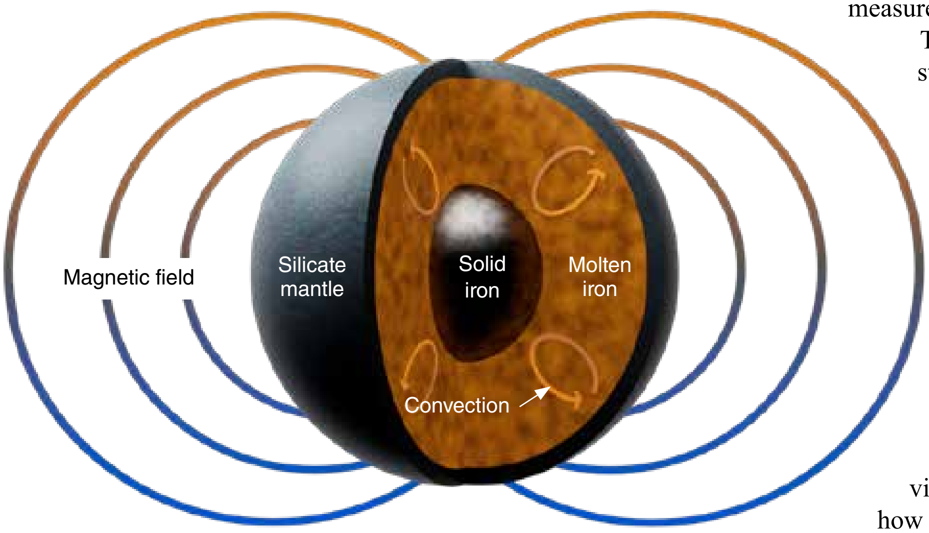
Intense Temperatures and Pressures

NIF Discovery Science Program researchers, led by Livermore physicist Rick Kraus, have been working to determine how and when cores of super-Earths solidify and their magnetospheres cease. Building on decades of developments at NIF including exquisite laser pulse shaping, plasma x-ray source generation, and the TArget Diffraction In Situ (TARDIS) x-ray diffraction diagnostic, the team determined the high-pressure melting curve and structural properties of pure iron up to 1,000 Gigapascals (GPa), a pressure nearly four times greater than any previous experiment and three times the pressure at the center of the Earth. For these experiments, the team aimed pulses of 16 NIF laser beams on a sample package of beryllium, germanium, pure iron, and lithium fluoride, shocking the iron into a liquid state between 220 and 300 GPa. Following the initial shock, the team carefully increased the laser power, so as to compress the iron with only a small temperature increase, which drives the iron back toward the solid state at high pressure. Finally, using x-ray diffraction, the team assessed whether the compression wave had resolidified the iron.

An artist's rendering of the cross section of a super-Earth with the National Ignition Facility (NIF) target chamber superimposed over the mantle. (Image credit: John Jett.)

Expert target fabrication played a critical role in the success of the experiments and required NIF's technological capabilities as well as the expertise of its researchers. Each sample package was designed to subject an iron sample to a single, steady shockwave. "As the shock from the NIF lasers moved from the iron to the lithium fluoride window, the iron decompressed slightly, ensuring a completely liquid iron sample for all but the lowest shock pressure experiment. Then we precisely increased the laser power to isentropically compress the sample to the desired peak pressure, up to 1,000 Gigapascals in about 10 nanoseconds, where we measured the initial shock pressure and peak pressure in the sample," says Kraus, who was recently awarded the inaugural American Physical Society's 2023 Neil Ashcroft Early Career Award for Studies of Matter at Extreme High-Pressure Conditions. To document the structure of iron at peak pressure, another 24 beams of the NIF laser illuminated a germanium or zirconium foil, producing a hot plasma, which emitted a nanosecond burst of radiation, allowing the team to record an x-ray diffraction snapshot within the TARD IS diagnostic. The pinhole of palladium or platinum attached to the sample package collimated or aligned the x rays and cast a known diffraction pattern.

Jon Eggert, chief scientist in the High-Energy Density (HED) section, led the development and fielding of the NIF TARDIS diagnostic, which uses x-ray diffraction to determine crystal structures, measure density, and evaluate strain-induced texturing of iron at extreme conditions. "This campaign required determining the precise pressure history and distribution within a target. To predict and control the sample pressure, we used advanced radiation hydrocode simulations similar to those used for inertial confinement fusion and the Laboratory's Weapons and Complex Integration computational models. We then improved our predictive tools by reconciling our results with each successive shot," says Eggert.



A dynamo of molten iron generates the Earth's magnetic sphere that protects the planet from lethal solar rays and cosmic radiation. Understanding the melting curve of iron under conditions similar to the core of rocky planets and super-Earths helps scientists characterize the potential for these planets to have sustained dynamo-generated magnetospheres and the potential to support life. (Renderings by Eric Smith).

Solid in a Nanosecond

By harnessing the ultra high-power laser capabilities and diagnostics of NIF, Kraus and his team produced unprecedented pressures and temperatures, tracing the melt curve and crystallization process of iron at the extreme conditions within a super-Earth. At approximately both 550 and 1,000 GPa, the team observed a transition from liquid iron at high entropy states to a solid-hexagonal, close-packed (hcp) crystalline structure as the pressure rose, which means that the cores of exoplanets solidify from the bottom up and produce stronger magnetic fields that do a better job of protecting planetary surfaces from charged particles. "Although our data are focused on iron melting in super-Earth cores, our results also provide accurate determination of iron melting at the pressure-temperature conditions from the bottom of Earth's core through the inner core boundary, which has been controversial because of the lack of ability to directly take measurements in these conditions," says Kraus.

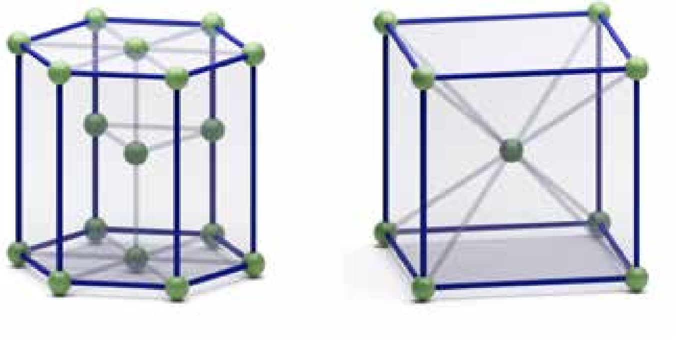
The fundamental processes for nucleation—the first step in the solidification of iron—and crystal growth at extreme conditions remains a challenging theoretical field. Jon Belof, group leader in the Materials Science Division and project lead for the theoretical and simulation studies of phase transformation kinetics, explains, "The timescale of planetary formation of an iron core is considerably slower than those we've attained with the very short timescale of compression experiments on the NIF. The development of a physics-based model for the nucleation process, considering this change in compression rate, has been a multiyear effort at the Laboratory." By applying extremely fast compression via laser drivers, the limits of theoretical understanding for how phase transformations occur at extreme conditions shed new light on this complex, dynamic process.

Livermore has also determined through these experiments that iron solidification happens very quickly, rather than over long periods of time. At Earth's core, scientists have questioned how it is possible for the Earth to have a solid inner core, hypothesizing based on previous experiments that iron must be supercooled by 2,000 Kelvin before it solidifies, implying Earth should not have a solid inner core even on a few billion-years' timescale. The NIF experiments, however, revealed that iron solidifies at near equilibrium and on a timescale of nanoseconds. "The fact that you can observe near-equilibrium solidification of iron at such short timescales addresses an interesting paradox. People questioned why Earth has a solid inner core if it required significant supercooling before solidifying, but we can take the results from our experiments and show that this theory of long cooling times is incorrect. Rather than taking billions of years to solidify iron, it takes only billionths of a second," says Kraus.

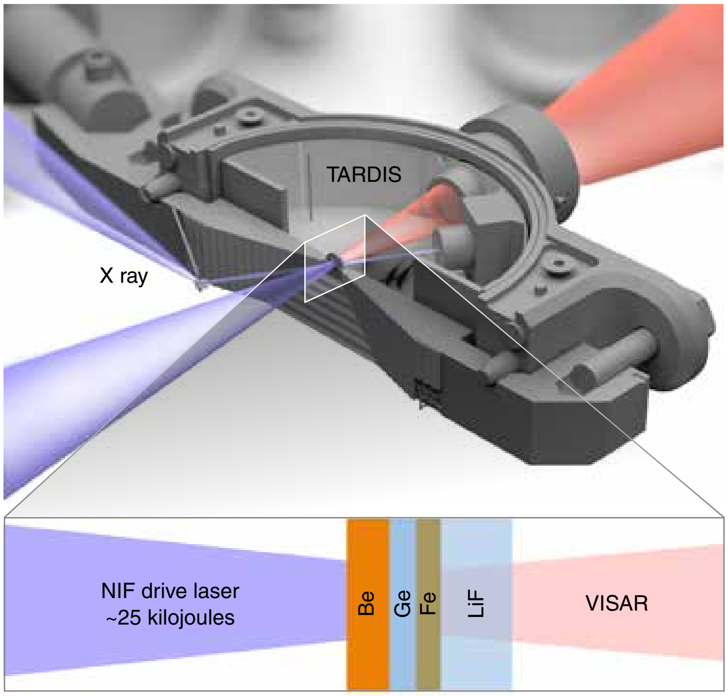
The team's observations of pressure-driven solidification indicate super-Earths will undergo bottom-up solidification, which will produce stronger magnetic fields than outside-in solidification. With nascent liquid iron cores and a nominal core-mantle boundary heat flux, the team found that super-Earth cores will take up to 30 percent longer to solidify than Earth's core, while cores of planets smaller than Earth will solidify faster. "Assuming solidification sets the timescale for dynamos, our results lead to the notable finding that super-Earths are likely to have a longer duration of magnetically shielded habitability than Earth," says Kraus.

What's Next?

Documenting the melting temperature of iron in the Earth's core is important because it sets our understanding of the heat balance and physical conditions within the Earth as well as how it impacts the core's structure. "Determining that the structure of solid iron near the melt point is hcp rather than body-center cubic (bcc) is a huge deal because it helps geologists and geophysicists understand key inferences about the Earth's core," says Kraus. "Seismologists infer that sound waves move faster in the core depending on their direction, or anisotropy." Scientists are working to put the puzzle pieces together regarding fundamental anisotropy within hcp and bcc crystals versus what is seen in the core and what that reveals about the composition of the inner core and its thermal history.



The Livermore team determined that iron near the melt point transitions from liquid to a mixture of liquid and solid hexagonal close-packed (left) crystalline structures rather than body-centered cubic (right). This finding will help geophysicists and seismologists understand more about the Earth's core.



Livermore's research team used NIF and in situ x-ray diffraction to discriminate between phases of matter at extreme conditions using the TArget Diffraction In Situ (TARDIS) diagnostic, with a zoomed-in view of the sample package with layers of Beryllium (Be), germanium (Ge), iron (Fe), and lithium fluoride (LiF) that is attached to a collimating pinhole at the front of the TARDIS. The Velocity Interferometer System for Any Reflector (VISAR) produces data that determines the initial shock pressure.

Despite the significant results that Livermore has uncovered through these experiments, questions persist. The team plans to explore what factors contribute to the stability of materials under extreme conditions, whether those materials behave as insulators or metals, as crystalline solids or liquids, and whether they form mixtures or segregate. "We've been able to put together a more complete understanding of how iron solidifies over a range of super-Earth masses, the timescales for core solidification as well as how long a planet could have a magnetosphere, but this is just the beginning," says Kraus.

—Sheridan Hyland

Key Words: body-centered cubic (bcc), dynamo, hexagonal close-packed (hcp), magnetosphere, National Ignition Facility (NIF), super-Earth, TArget Diffraction In Situ (TARDIS), Velocity Interferometer System for Any Reflector (VISAR).

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