

# The Heat is On: Thermal Transport and Melting

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1811-5209/26/0022-089\$2.50 DOI: 10.2138/gselements.22.2.89

Heat can induce melting in planetary interiors, transforming a solid crystal lattice into an amorphous liquid magma. IMAGE CREDIT: J.M. JACKSON.

**H**eat is a fundamental driver of planetary evolution, shaping its interior, surface, and atmosphere. On Earth, the flow of heat powers dynamic systems that are essential to life. Thermochemical variations across the core–mantle boundary play an important role in regulating heat flow, which influences the dynamics of both the mantle and the core, including generation of the geodynamo. In this article, we focus on thermal transport and melting, including highlights of new technological developments in laboratory optics and synchrotron facilities. Here, we offer a perspective that highlights the spatial and temporal characteristics of these processes, where new developments expand our understanding of Earth’s thermochemical evolution, and hold promise for applications to other planetary bodies.

KEYWORDS: thermal transport; thermal conductivity; melting; diamond anvil cell

## THE IMPORTANCE OF HEAT IN A PLANET

Heat plays a crucial role in shaping a planet’s internal dynamics, surface activity, and long-term evolution. Thermal transport or the flow of heat connects the planet’s physical structure, its chemical evolution, and its potential to support life (FIG. 1). Every planet, including Earth, behaves like a cooling body, gradually losing heat accumulated during formation and evolution. Earth’s inner core is the hottest region, with temperatures comparable to the Sun’s surface. As heat moves outward through the mantle and crust, thermochemical boundary layers impede heat flow, with thermal resistance driving powerful planetary processes.

Earth functions like a giant heat engine, converting thermal energy into mechanical work responsible for life-supporting processes:

- Circulation of molten iron alloy in the outer core creates Earth’s geomagnetic field, protecting the planet from harmful solar and cosmic radiation.
- Mantle convection drives plate tectonics, recycling resources through subduction and volcanism, while causing earthquakes, building continents, and regulating surface chemistry.
- Atmospheric circulation is powered by heat from Earth’s crust and solar radiation, shaping wind systems, climate patterns, ocean currents, and ecosystems.

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Earth’s sustained heat flow has fueled long-term tectonic and magnetic activity—both crucial for habitability. Other planetary bodies with different sizes, impact histories, and compositions, like Mars and the Moon, likely had a different thermal history and currently lack active magnetic field-generating cores and plate tectonics, making them less hospitable to life.

Heat flow further induces melting in certain regions of the mantle and crust. Partial melting is crucial for chemical separation and material evolution: when rocks partially

melt, each chemical element behaves differently—some preferentially enter the melt, while others remain in the solid residue, depending on pressure, temperature, and bulk composition. This selective separation results in chemical differentiation, creating distinct layers at multiple scales. For example, Earth’s oceanic crust and continental crust differ significantly in composition from the bulk mantle that produces them through partial melting. Over time, this process concentrates minor and trace elements, often forming valuable metal ores and critical mineral deposits. Understanding where and how these processes occurred helps target resource exploration.

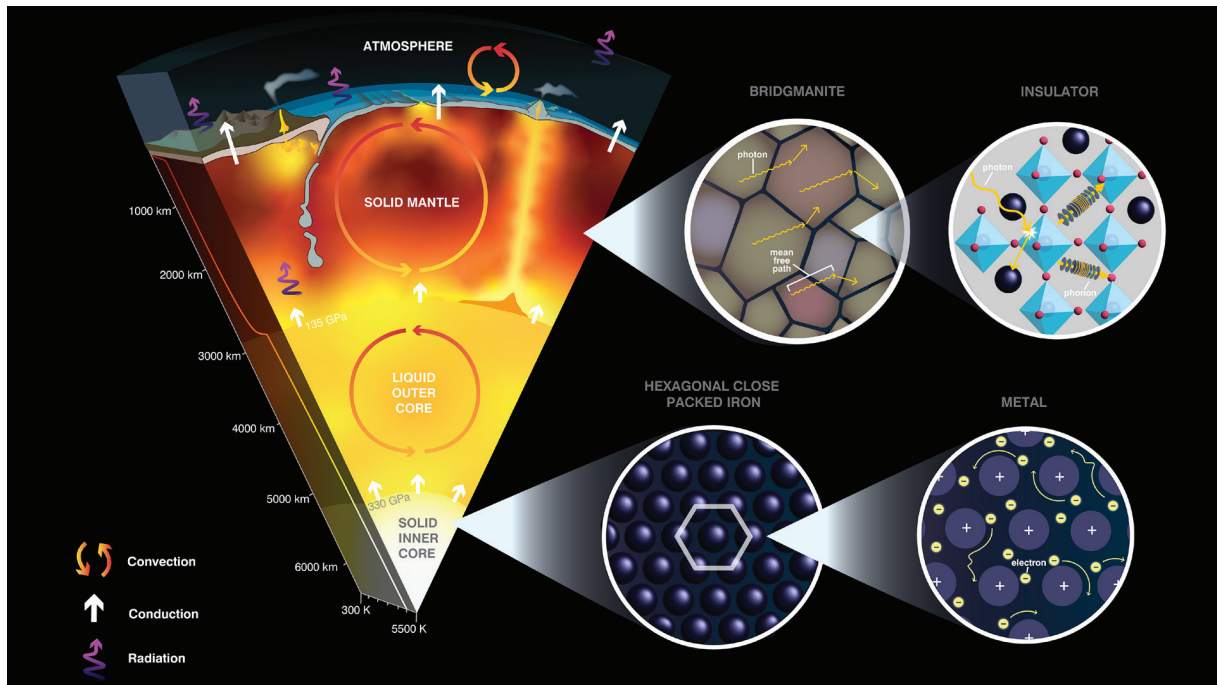
Heat flow and melting are central to addressing a fundamental question in Earth and planetary sciences: How do heat and mass transfer make Earth a habitable planet? Addressing this question requires understanding how heat flow through a planet produces mechanical work and melting processes (FIG. 1).

## WHAT IS HEAT?

### A Macroscopic Perspective

At the **macroscopic**\* scale, heat is a form of energy associated with the collective thermal motion of many particles. Although sometimes used to describe a material’s temperature, heat in thermodynamics refers to energy transferred between systems due to temperature differences or phase changes. It is not a material substance, rather a macroscopic quantity emerging from the statistical behavior of large ensembles of atoms and molecules.

\* Definitions of terms presented in **blue** are given in the glossary on page 81; terms in **orange** are described in Box 1.



**FIGURE 1** Modes of heat transfer in the Earth across scales. Convection in the mantle involves slab subduction and plume upwelling, driving chemical cycling and continent building. Convection in the outer core generates Earth's magnetic field. Conduction is dominant where convection is suppressed (brittle lithosphere, inner core, and boundary layers), while radiation is important at the surface and possibly in the deep mantle. At the small scales of grains and atoms, mantle rocks are dominated by insulating minerals like bridgmanite, in which heat is transferred primarily by phonons (disks along the arrows represent density fluctuations) and photons. Bridgmanite, like many mantle minerals,

exhibits relatively low thermal conductivity (ambient: 8 W/m/K; CMB: 10 W/m/K) but can have relatively high melting temperatures (ambient: 1883 K; CMB: 5170 K). In contrast, the core is made of metallic iron alloys, where electrons are the primary heat carrier, with relatively high thermal conductivities (76 W/m/K at ambient; 35–180 W/m/K reported at CMB conditions). The melting temperature of iron (1808 K at ambient; 3470–4270 K reported at CMB) and its alloys constrain the temperature at the solid-liquid inner core boundary (*hcp*-Fe: 5500 K; Sinmyo et al. 2019). See online supplement for references to these values.

Heat is transferred through three primary mechanisms: **convection**, **conduction**, and **radiation** (FIG. 1). Thermal energy in a system can be modulated via several key mechanisms. Heat of accretion, generated during planetary formation by impacts and gravitational compression, plays the most significant role early in a planet's history. Tidal heating, relevant to some planetary bodies like Jupiter's moon Io, originates from gravitational flexing from nearby massive objects. Heat can be absorbed by endothermic processes, like mantle melting or atmospheric evaporation. Secular cooling and radiative loss, where heat is continuously lost to space through Earth's surface and atmosphere, operate over geological time-scales, affecting tectonics, volcanism, and core dynamics.

In the modern Earth (FIG. 1), convection dominates in the liquid outer core (driving the geodynamo and Earth's magnetic field), the solid-but-ductile mantle (driving plate tectonics and volcanism; Mazzucchelli et al. 2026 this issue), and the atmosphere (driven by surface heating and solar energy). Conduction dominates where convection is inefficient or suppressed, like the crust (especially the rigid lithosphere) and the solid inner core. Thermal-chemical boundary layers, such as in the lowermost mantle (D'' layer), offer a complex partition between conduction and convection. Latent heat is important in the growth of the inner core, where latent heat of crystallization helps drive convection and the geodynamo. Similarly, latent heat is also involved in melting/freezing in the mantle and crust, relevant during magmatism or subduction. Radiation is relevant at Earth's surface, where thermal energy is radiated into space, and perhaps also in the deep mantle (see below). Radiogenic heat, an ongoing source from radioactive decay of long-lived isotopes (e.g., uranium, thorium, potassium-40), is a major contributor to Earth's

present-day heat budget. Measurements of Earth's heat flux show lower values through thick continental crust (using borehole thermal measurements) and higher at mid-ocean spreading centers (using vent fluid analysis), with ~87 mW/m<sup>2</sup> as a global average surface heat flux (Pollack et al. 1993).

### A Microscopic Perspective

At the **microscopic** scale, heat originates in (and temperature quantifies) the uncorrelated motions of atomic-scale particles (**electrons**, nuclei). Concisely, the density matrix is diagonal in the eigenstates of the **Hamiltonian**, with weights given by Boltzmann factors parameterized by temperature (Box 1). This perspective is useful

#### Box 1 MICROSCOPIC HEAT TRANSFER

**Electrons:** major heat carriers in metals and degenerate semiconductors. Electron motion under thermal gradients leads to energy transfer, which is governed by the Wiedemann-Franz Law in metals:

$$\frac{k_e}{\sigma T} = L,$$

where  $k_e$  is the electronic thermal conductivity (W/m·K),  $\sigma$  the electrical conductivity (S/m),  $T$  temperature (K), and  $L$  Lorenz number.

**Photons:** act as carriers in radiative heat transfer, especially in vacuum and optical materials. Dominant at high-temperature (e.g., blackbody radiation). Photons carry energy across large (astronomical) distances.

**Density matrix:** represents the distribution of quantum states in a physical system.

**Hamiltonian:** the total energy operator (sum of kinetic and potential energy).

**Quasiparticle:** entity representing the collective behavior of many interacting particles (e.g., phonons, magnons).

to understand the transfer of heat between interacting particle ensembles. In electrically conducting materials, electronic excitations near the Fermi level contribute and sometimes dominate. **Phonons**, a quantum mechanical concept of **quasiparticles** encoding atomic vibrations, are the main carriers of heat in insulators and semiconductors. For many solids, their motion and scattering behavior dominates thermal conductivity. Magnetically ordered materials harbor yet another quasiparticle excitation described by **magnons**.

Modulation of atomic-scale thermal transport is an important consideration for heat transfer in planetary bodies. Central to this is the mean free path (MFP) concept—the average distance a particle or quasiparticle travels before scattering. Shorter MFPs mean lower thermal conductivity. At low temperatures, weak phonon-phonon scattering leads to long MFPs and high conductivity; while at high temperatures, and from a simplistic view, increased scattering occurs (**Umklapp processes**), shortening the MFP and reducing conductivity. Electron-phonon scattering similarly lowers electrical and thermal conductivity in metals at high temperature ( $T$ ). Although the Wiedemann-Franz Law links electrical and thermal conductivity in metals (BOX 1), it breaks down in low-dimensional materials, strongly correlated electron systems, and at very low temperature due to quantum effects.

Spanning orders of magnitude in scale, **impurities** and grain boundaries disrupt lattice periodicity and act as scattering centers, setting up a link between the scale of the scatterer and that of the MFP for the relevant heat carrier. Most minerals contain impurities that shorten the MFP, so their thermal conductivity is generally low. Impurities in metals cause elastic scattering, thereby increasing electrical resistivity. This is important for thermoelectrics, where low thermal conductivity is desired without harming electrical performance. Nevertheless, metals like iron alloys typically have higher conductivity, but more complex  $T$ -dependence. Radiative conductivity, which increases with  $T^3$ , becomes significant at depth in minerals that are translucent for wavelengths around  $2.9/T$  (mm·K) where **photon** MFPs can be millimeters—much longer than nanometer-scale phonon MFPs. In such cases, grain-size effects (due to grain boundary scattering) are important for radiative conductivity but less so for phonons.

Let's compare bridgmanite and iron, which are representative phases in Earth's deep interior (FIG. 1). Bridgmanite, the dominant mineral in Earth's lower mantle, conducts heat primarily via phonons, typical of insulating silicates. As a potentially translucent material, its thermal conductivity may also be facilitated by photons, where these mechanisms depend on pressure, temperature, and impurity concentration ( $\text{Fe}^{2+}$ – $\text{Ti}^{4+}$  and  $\text{Fe}^{2+}$ – $\text{Fe}^{3+}$  intervalence charge transfer bands; e.g. Evans and Rossman 2024). In contrast, iron, the main component of the core, is dominated by electronic thermal conduction, in which the free electrons are the primary heat conductors. This fundamental difference in conduction mechanisms reflects the contrasting physical nature of the two materials: insulating and potentially translucent for

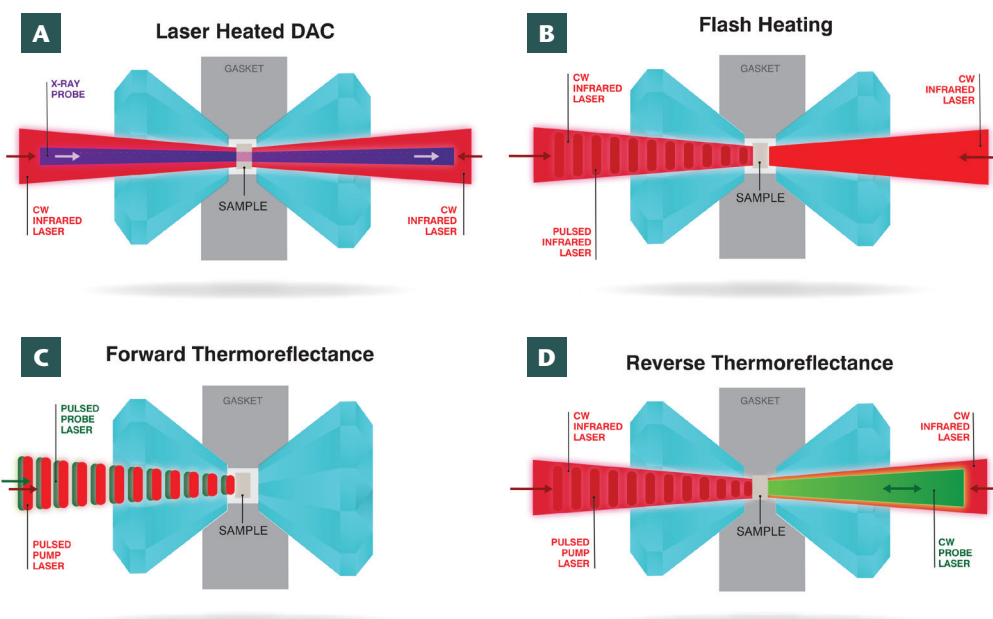
bridgmanite versus metallic, conductive, and opaque for iron. At ambient conditions, the thermal conductivity of pure iron is about 10 times higher than that of bridgmanite.

## MODERN PROBES OF THERMAL TRANSPORT AND MELTING

Studying thermal transport and melting in planetary bodies requires generating the extreme pressures and temperatures of deep planetary interiors in a laboratory setting. The workhorse tool for high-pressure experiments is the diamond anvil cell (DAC)—a device that squeezes microscopic samples between the polished tips (“culet”) of two diamonds (FIG. 2). Because pressure is defined as force over the area it is applied, the DAC can leverage modest forces concentrated over the tiny culet areas to compress samples from room pressure to pressures beyond Earth's center (>3.5 million atmospheres). Diamonds are not just hard, stabilizing pressure generation, but also transparent to most wavelengths of light, letting researchers focus infrared lasers on samples to generate thousands of degrees of temperature. Hot samples radiate thermal emission that is recorded as a spectrum of intensity versus wavelength to constrain the sample temperature. By combining these tools with X-ray methods, researchers can probe various physical and chemical aspects of samples in situ at extreme pressure–temperature conditions (see Campbell 2026 this issue; Öztürk et al. 2026 this issue).

### Thermal Transport

The small size of DAC samples presents unique challenges for traditional thermal transport experiments. The main issues are establishing contact of samples with heating sources and thermocouples, while working at the very rapid time scales of thermal diffusion across microscopic distances. At the same time, diamond's transparency has allowed for significant developments of optical methods (Zhou et al. 2022) that combine pulsed laser heating with rapid temperature measurements using thermal emission or a proxy, such as reflected laser intensity. The general



**FIGURE 2** Schematic illustrations showing methods for performing XRD and thermal conductivity measurements on a material in a DAC. (A) Combination of continuous wave (CW) infrared laser heating and XRD; (B) flash heating method; (C) forward-type thermoreflectance method; and (D) reverse-type thermoreflectance method. In (C), the pump and probe lasers are colored differently for ease of viewing, but the actual wavelengths are the same.

approach involves (i) inducing a transient temperature gradient in the sample, (ii) monitoring the time evolution of temperature at one or more locations to observe thermal diffusion, and (iii) fitting the temperature response to a diffusion model that incorporates sample chamber geometry to extract the sample's thermal conductivity. We highlight a few different experimental configurations that have been developed in recent years for measuring thermal transport in DACs at high pressure.

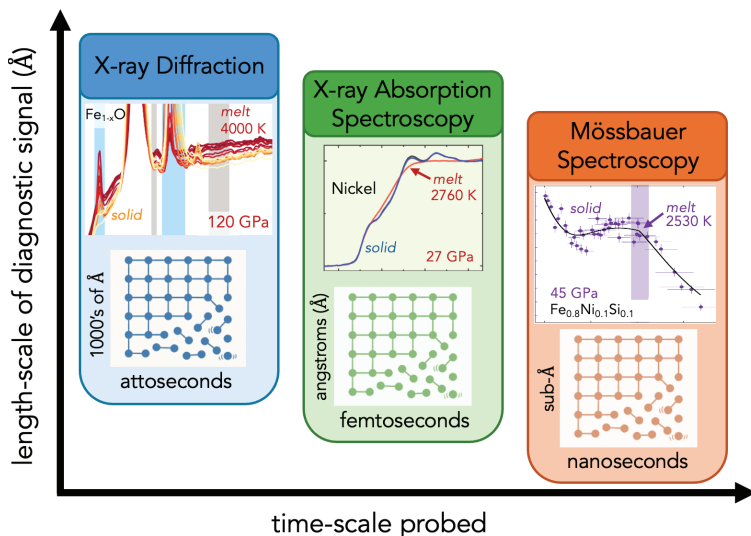
The “flash heating” method involves first heating a sample from both sides with a continuous laser to establish a baseline temperature relevant to planetary interiors. A fast laser pulse (~1 microsecond) is then applied to one sample surface. Temperature initially rises on the pulsed side, followed by thermal diffusion through the sample, leading to a delayed temperature increase on the non-pulsed side. A high-speed photodetection device is used to measure how temperature evolves on both sides of the sample. In this method, temperature is constrained from the thermal emission, and both heating and subsequent cooling of both sides are measured (Geballe et al. 2020). This brings reliability in measuring thermal diffusion but also challenges inherent to thermal emission measurement. Sufficient photons for precise temperature determination are only viable above ~1500 K. Typical magnitudes of laser pulses produce transient temperature variations of ~100 to 400 K.

The other set of approaches can be grouped as “thermoreflectance” methods. Instead of directly measuring temperature evolution, these methods rely on changes in the reflectivity of materials (especially metals) with temperature. To achieve this, a “probe” laser pulse (often ~1 nanosecond) shines on a sample surface (or a thin metal layer on the sample surface), with measurements recording the changes in its reflected intensity. Two main forms of thermoreflectance are recognized: one involves observing sample cooling on the same pulsed side of the sample (forward type) (Hsieh et al. 2020); the other involves observing sample heating on the reverse side (reverse type) (Hasegawa et al. 2024) (FIG. 2). The former is generally limited to room temperature or slightly elevated temperatures. On the other hand, recent progress has combined the latter approach with continuous laser heating to reach extreme temperatures, as with flash heating. Although temperature is not directly measured, these methods hold the advantage of allowing for temperature pulses as low as 5 K and measurements from room to high temperatures.

Radiative heat conduction in the deep mantle may also be significant. The factors determining heat transport by optical radiation are the photon absorption/emission process and the radiation spectrum. Consequently, thermal conductivity by photon interaction is calculated from the optical absorption coefficient of the sample, determined by optical absorption spectroscopy (Solomatova et al. 2026 this issue), where in situ experiments at high temperatures and pressures in the DAC have yielded estimates for the thermal conductivity by photon interaction of major mantle minerals (Lobanov et al. 2017).

## Melting

Melting is a first-order phase transition in which a solid transforms into a liquid. For a single-component system like pure iron, this process occurs at the melting point (or fusion point), where solid and liquid phases are in thermodynamic equilibrium at a specific temperature and pressure. An increase in entropy occurs upon melting because the liquid state has more disorder than the crystalline solid (entropy of fusion), while a change in enthalpy reveals that heat must be absorbed by the solid to break its



**FIGURE 3** Spatiotemporal description of the time-scale probed and length-scales of in situ melt-detection methods described here. Nonresonant X-ray diffraction represents very fast snapshots (attoseconds;  $10^{-18}$  s) of the material's atomic spatial configurations, requiring several unit cells (1000s of angstroms) to achieve diffracting conditions and similar length-scales to observe liquid diffuse scattering (Dobrosavljevic et al. 2023). Described by the Lamb-Mössbauer factor ( $f$ ), melting in Mössbauer spectroscopy is diagnosed when iron's thermal motions stray from their equilibrium positions farther than 0.14 Å during the nuclear resonance lifetime (nanoseconds;  $10^{-9}$  s) (Dobrosavljevic et al. 2022). The Debye-Waller factor describes thermal motions in X-ray diffraction in an analogous way to the Lamb-Mössbauer factor. The intermediate length- and time-scales are sampled by X-ray absorption spectroscopy (Boccatto et al. 2017), a resonant technique at the eV scale (femtoseconds;  $10^{-15}$  s).

atomic lattice bonds. In this section, we describe modern probes that access the different time and length scales of the melting process (FIG. 3).

Melting experiments in DACs commonly combine (i) infrared lasers to heat samples for seconds to minutes, and (ii) a probe to detect the transition from solid to molten states. Early work relied on optical probes like visual observation of apparent sample motion, changes in sample surface reflectivity, or a plateau in sample temperature with increasing laser power. Optical probes, however, sense phenomena other than melting—recrystallization, deformation, or any change affecting light absorption or heat capacity. Models of heat flow in DACs (Geballe and Jeanloz 2012) have shown that only extremely rapid (microsecond time-scale) experiments are fast enough to observe true latent heat signatures in extremely small (micron-scale) sample chambers (Geballe et al. 2021).

Breakthroughs in high-pressure techniques have been achieved thanks to the development of synchrotron X-ray methods (Campbell 2026 this issue; Öztürk et al. 2026 this issue). Compared with optical probes, X-rays have two key advantages: sensitivity to the bulk sample and direct access to atomic-scale structure and dynamics across a range of length and time scales. Micron-scale beams with high fluxes and sensitive photon detectors together allow probing of small DAC samples heated to extreme temperatures over short times (~1 second) with multiple techniques. Here we highlight three X-ray scattering methods that can reveal a solid-liquid transition from different spatial and temporal perspectives.

X-ray diffraction (XRD) involves scattering of photons by a sample's electrons. In crystals, atoms are ordered in periodic lattices over length scales much longer than

the spacing between atoms. For specific combinations of photon wavelength and scattering angles, incident photons are diffracted by parallel lattice planes such that scattered photons constructively interfere. This produces strong reflection intensities at specific angles, overlain on a broad background mostly produced by Compton scattering from the diamond anvils. In a liquid, long-range order is absent, but short-range order (over length scales similar to atomic spacing) is retained. Upon melting, the discrete reflections at specific scattering angles are replaced by a broad “liquid diffuse signal” (Anzellini et al. 2013), that can also give insight into liquid structure (Eggert et al. 2002). In principle, XRD provides a general method applicable to a wide set of materials. However, detecting subtle liquid signals above a large noisy background can pose a significant challenge, leading to possible overestimation of melting temperatures if care is not taken to quantify background shape and variation during experiments.

X-ray absorption spectroscopy (XAS) involves excitation of a core electron by an incident photon with the same energy as the binding energy of the electron. When the photon is absorbed, the core electron is excited from its ground state to the lowest empty state (referred to as a “photoelectron”), while a different electron can decay into the core hole, emitting a measurable photon of specific energy. XAS is an element-selective technique that considers changes to the absorption spectrum at the absorption edge—the energy at which particular electron excitation and photon fluorescence begins (7.112 keV for iron’s “K-edge”). The absorption spectrum of condensed matter can exhibit fine structure at and above the edge caused by the wave-like nature of the electron—it can be backscattered by atoms surrounding the absorbing atom and lead to interference effects. Near-edge structure is thus sensitive to the atom’s local environment, containing structural and electronic information. While sometimes applied to study features like oxidation states of iron, XAS has been recently applied to melt detection by observing empirical changes in the fine structure of the spectrum (Boccatto et al. 2017; Torchio et al. 2020).

Synchrotron Mössbauer spectroscopy involves excitation of an atomic nucleus, commonly in the  $^{57}\text{Fe}$  isotope of iron, by absorption of an incident photon and subsequent re-emission upon nuclear decay back to the ground state. In a liquid or gas, the incident photon both excites the nucleus at its specific transition energy (14.4 keV) and transfers some momentum to the nucleus. However, when the iron atom is bound within a solid (either crystal or glass), a significant fraction of events occurs with no transfer of momentum (“recoil-free” absorption) (Mössbauer 1958). The emitted photon then has the same momentum and energy as incident photons, just with a time delay induced by the scattering process. By using a time discrimination approach, one can isolate the signal, produced exclusively by solid-bound  $^{57}\text{Fe}$  atoms (given by the Lamb-Mössbauer factor,  $f$ ). The intensity of the signal is inversely proportional to the mean-square displacement of the nucleus during its excitation lifetime (141 ns). When the iron atoms stray from their equilibrium positions much farther than  $1/k = 0.14 \text{ \AA}$  (where  $k$  is the wave number at 14.4 keV) during the nuclear lifetime, the value of  $f$  becomes exponentially small. When melting occurs in a sample, the measured intensity exhibits a discontinuous drop, as the nuclei transition from relatively fixed to mobile in space (Singwi and Sjölander 1960; Jackson et al. 2013).

### **A Spatiotemporal Perspective**

Utilizing a single technique like the ones described above has become common practice to constrain the melting point (or solidus for multi-component systems), primarily

due to the significant challenges of such experiments under extreme conditions. Combining multiple in situ techniques, however, provides access to different time and length scales of the involved atomic arrangements, thereby enhancing understanding of the materials being studied, while robustly constraining the melting transition (FIG. 3). For example, independent X-ray diffraction and Mössbauer experiments have recently been combined on the same sample configurations to place tight constraints on the solidus of deep Earth materials (Dobrosavljevic et al. 2022, 2023).

## **APPLICATIONS TO EARTH AND PLANETARY SCIENCE**

### **Deep Planetary Temperatures**

Melting experiments provide important constraints on the thermal state of Earth’s deep interior. Determining temperatures for the core and core–mantle boundary (CMB) is a major challenge from an observational perspective, so scientists use the solid–liquid inner-core boundary (ICB) as a reference. Located at 330 GPa (FIG. 1), the ICB marks the solidus of the core’s iron alloy, anchoring the temperature profile of the outer core. High-pressure melting studies of iron alloys therefore help constrain core temperatures. These alloys, based on geophysical observations and geochemical data, typically contain ~5%–10% nickel and light elements like oxygen, silicon, hydrogen, carbon, and sulfur. A recent spatiotemporal melting study was performed on the *face-centered cubic* phase of  $\text{Fe}_{0.8}\text{Ni}_{0.1}\text{Si}_{0.1}$  (Dobrosavljevic et al. 2022), a representative composition of Earth’s and Mercury’s cores (FIG. 3), placing constraints on a lower bound temperature of 3500 K for the Earth’s CMB.

### **Powering Magnetic Fields**

While melting experiments on iron alloys reveal current core temperatures, thermal transport experiments are key to understanding its history. Core thermal conductivity influences whether convection (the geodynamo) can operate. The conductivity of the outer core liquid competes against the CMB heat flow—the amount of heat transported out of the core by mantle convection. If dense liquid iron alloys are highly conductive, then the outer core can conduct heat efficiently and accommodate the entire CMB heat flow. But if the liquid alloy has a low conductivity, then conduction alone is not efficient enough to bring heat from the inner core to the cooling mantle base. Instead, convection is initiated and sustained in the outer core, powering the geodynamo in this process of “thermal convection.” High-pressure experiments thus aim to measure the conductivity of iron alloys under core conditions, which are revealing higher conductivities than previously thought (Landeau et al. 2022; Ohta et al. 2025).

The history of Earth’s core is also strongly linked to the freezing and growth of the inner core. Because Earth’s magnetic field is known to have operated for at least 3.4 billion years (Fu and Harrison 2026 this issue), researchers explore how it persisted even with high conductivity. Two key processes are the release of latent heat during inner core growth and the enrichment of light elements in the liquid, both of which influence buoyancy and drive convection. Experiments focus on light element partitioning during melting and the thermal effects of solidification, helping to constrain when the inner core began crystallizing and how hot the early core was.

The deepest mantle may have hosted a long-lived “basal magma ocean” (BMO), potentially capable of driving an early geodynamo through convection (Stixrude et al. 2020). The BMO’s longevity and dynamics depend on its

evolving composition, temperature, and conductivity. Applying modern melting and thermal transport experiments to increasingly complex petrologic systems helps address major questions about Earth's deep history. The BMO may also concentrate heat-producing elements, making the lowermost mantle a key thermal reservoir that affects the cooling histories and dynamics of both mantle and core.

### Earth's Lowermost Mantle

Melting and thermal transport experiments are necessary to understand the complex landscape of multi-scale structures at Earth's mantle base (Jackson and Thomas 2021). Due to the chemical complexity and heterogeneity of this region, even small changes in temperatures can lead to big changes in mineral assemblages and compositions. Compositional and thermal variations can interact to produce localized partial melting, promoting further chemical partitioning and differentiation, in analogy to crust production at the surface and, in turn, have major impacts on physical properties, like **viscosity** and conductivity. For example, the presence of strongly correlated electronic and conductive materials like FeO (Ohta et al. 2012; Ho et al. 2024) influences convective flows in the core and surface expressions of the magnetic field. These variations further influence basic aspects of chemical storage and flow in the Earth—how plumes are generated, how long they last and how mobile they are, the fate of subducted slabs at the mantle base, and slab interaction with deep chemical reservoirs or the outer core.

## FUTURE OUTLOOK

### Perspectives on Technical Development

This article highlights several cutting-edge methods for measuring thermal transport and melting in DACs under deep Earth conditions. Active research frontiers focus on (i) pushing accessible pressure and temperature conditions, (ii) improving accuracy and precision, and (iii) increasing throughput to systematically study how compositional changes affect melting and transport behavior. We touch on a few major directions of technical development.

- **Understanding and controlling temperature.** Efforts focus on improving temperature accuracy and understanding spatial temperature distributions. This includes using finite element modeling (Geballe et al. 2020) and advancing photon detectors for low-temperature sensitivity and microsecond heating (Andrault et al. 2025). Accurate temperature control is critical for interpreting thermal transport and melting, where detected X-rays may traverse both solid and liquid phases. Advancing electrical heating inside DACs improves thermal stability and reproducibility, both for longer-term (up to hours) (Sinmyo et al. 2019) and very rapid (as fast as a microsecond) heating (Geballe et al. 2021). Multi-technique studies help resolve discrepancies arising from heating, sample differences, or method-specific limitations (Dobrosavljevic et al. 2023).
- **Improving resolution in space and time.** The reduced X-ray beam size and higher flux in fourth-generation synchrotrons, as well as at free-electron laser facilities (Edmund et al. 2024), are enabling higher spatial and temporal resolution critical for small samples at megabar pressures and more complex chemical systems. Another aspect of spatial resolution is improving characterization of sample geometry using in situ optical and X-ray methods, such as white light interferometry and microtomography, to precisely determine the electrical and thermal conductivity (Ohta et al. 2020; Lobanov and Geballe 2022).

- **Pushing the limits on pressure.** Developments in double-stage DACs and shaping diamond anvil surfaces (e.g., “toroidal” anvils) are opening the door to measurements beyond the Earth's center (364 GPa) into the terapascal regime. Various forms of dynamic compression, including the use of an X-ray free-electron laser (XFEL) and laser-driven ramp compression, can reach ultra-extreme conditions up to terapascals in pressure and 10,000s of degrees in temperature (White et al. 2025).

- **Increasing throughput in high-pressure science.** The microscopic scale of experiments brings challenges with physical preparation of sample chambers, an effort often as demanding as experiments themselves. The use of computer-controlled equipment (“micromanipulators”) offers a step away from entirely manual preparation. Future efforts are likely to include sample preparation via sputter deposition (Oka et al. 2024), as well as the development of automated and/or robotic systems for micro-assemblies in the style of “smart manufacturing”. In parallel, *ab initio* methods are seeing exciting new horizons thanks to coupling with machine learning (Stixrude 2026 this issue), speeding up calculations on larger atomic systems. The combination of large-scale computing with targeted experiments will be critical for expansive systematic studies of complex physical and chemical systems.

### Outstanding Questions

Over the past 4.6 billion years, Earth's internal heat transport has changed to shape the atmosphere, ocean, and life. The types of measurements described here are important to understand planetary evolution and observations of exoplanets. The range of exoplanets and their properties discovered to date broadens the space of compositions (and  $P$ - $T$ ) that need to be explored. For example, common insulators on Earth, like bridgmanite, may become more electrically conductive or dissociate under conditions of larger rocky planets.

We conclude with a few big-picture questions: How have mantle convection and core cooling changed over time? How does mantle viscosity (influenced by temperature, pressure, mineralogy, and hydration) govern the length- and time-scale of convection, plume generation, and oceanic slab descent? How do thermal states of early Earth influence long-term tectonic and geodynamo evolution? Can exoplanetary magnetic fields be detected, and what thermal and compositional histories enable dynamo activity? Addressing these questions links mineral physics, geophysics, geochemistry, and comparative planetology. Research on Earth's thermal evolution is part of a larger effort to decode the thermal and magnetic histories of planets across the universe, potentially shedding light on their habitability.

## ACKNOWLEDGMENTS

We gratefully appreciate the National Science Foundation's support (EAR-2212068 and EAR-CSEDI-2303148, J.M.J.), the Carnegie Postdoctoral Fellowship (V.V.D.), and MEXT (24H00266, K.O.). We thank Chris McGuire and an anonymous reviewer for helpful comments that improved this article, Wolfgang Sturhahn and George Rossman for insightful discussions, and Katy Cain for the illustrations in FIGURES 1 and 2. We genuinely appreciate the editorial handling by Sumit Chakraborty, Esther Posner, and Patrick Cordier.

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## REFERENCES

- Andrault D, Pison Pacynski L, Monteux J, Gardés E, Mathieu A (2025) Long-lived magnetic field in earth-like terrestrial planets. *Physics of the Earth and Planetary Interiors* 360: 107315, doi: 10.1016/j.pepi.2025.107315
- Anzellini S, Dewaele A, Mezouar M, Loubeyre P, Morard G (2013) Melting of iron at Earth's inner core boundary based on fast X-ray diffraction. *Science* 340: 464-466, doi: 10.1126/science.1233514
- Boccatto S and 9 coauthors (2017) The melting curve of nickel up to 100 GPa explored by XAS. *Journal of Geophysical Research: Solid Earth* 122: 9921-9930, doi: 10.1002/2017JB014807
- Campbell A (2026) Community-driven management of synchrotron-based mineral physics facilities. *Elements* 22: 122
- Dobrosavljevic VV and 8 coauthors (2022) Melting and phase relations of Fe-Ni-Si determined by a multi-technique approach. *Earth and Planetary Science Letters* 584: 117358, doi: 10.1016/j.epsl.2021.117358
- Dobrosavljevic VV and 8 coauthors (2023) Melting and defect transitions in FeO up to pressures of Earth's core-mantle boundary. *Nature Communications* 14: 7336, doi: 10.1038/s41467-023-43154-w
- Edmund E and 38 coauthors (2024) The thermal conductivity of bridgmanite at lower mantle conditions using a multi-technique approach. *Journal of Geophysical Research: Solid Earth* 129: e2024JB028823, doi: 10.1029/2024JB028823
- Eggert JH, Weck G, Loubeyre P (2002) Structure of liquid water at high pressures and temperatures. *Journal of Physics: Condensed Matter* 14: 11385, doi: 10.1088/0953-8984/14/44/487
- Evans HV, Rossman GR (2024) Intervalence charge transfer in aluminum oxide and aluminosilicate minerals at elevated temperatures. *American Mineralogist* 109: 2152-2161, doi: 10.2138/am-2024-9343
- Fu RR, Harrison R (2026) Paleomagnetic recording at the grain scale. *Elements* 22: 111-117
- Geballe ZM, Jeanloz R (2012) Origin of temperature plateaus in laser-heated diamond anvil cell experiments. *Journal of Applied Physics* 111: 123518, doi: 10.1063/1.4729905
- Geballe ZM, Sime N, Badro J, van Keken PE, Goncharov AF (2020) Thermal conductivity near the bottom of the Earth's lower mantle: measurements of pyrolite up to 120 GPa and 2500 K. *Earth and Planetary Science Letters* 536: 116161, doi: 10.1016/j.epsl.2020.116161
- Geballe ZM and 5 coauthors (2021) Latent heat method to detect melting and freezing of metals at megabar pressures. *Physical Review Materials* 5: 033803, doi: 10.1103/PhysRevMaterials.5.033803
- Hasegawa A, Ohta K, Yagi T, Hirose K, Yamashita Y (2024) Inversion of the temperature dependence of thermal conductivity of hcp iron under high pressure. *Scientific Reports* 14: 23582, doi: 10.1038/s41598-024-74110-3
- Ho WGD and 5 coauthors (2024) Quantum critical phase of FeO spans conditions of Earth's lower mantle. *Nature Communications* 15: 3461, doi: 10.1038/s41467-024-47489-w
- Hsieh WP and 7 coauthors (2020) Low thermal conductivity of iron-silicon alloys at Earth's core conditions with implications for the geodynamo. *Nature Communications* 11: 3332, doi: 10.1038/s41467-020-17106-7
- Jackson JM and 9 coauthors (2013) Melting of compressed iron by monitoring atomic dynamics. *Earth and Planetary Science Letters* 362: 143-150, doi: 10.1016/j.epsl.2012.11.048
- Jackson JM, Thomas C (2021) Seismic and mineral physics constraints on the D'' layer. In: Marquardt H, Ballmer M, Cottaar S, Konter J (eds) *Mantle Convection and Surface Expressions*. American Geophysical Union, Washington, DC, pp 193-227, doi: 10.1002/9781119528609.ch8
- Landeau M, Fournier A, Nataf HC, Cébron D, Schaeffer N (2022) Sustaining Earth's magnetic dynamo. *Nature Reviews of Earth and Environment* 3: 255-269, doi: 10.1038/s43017-022-00264-1
- Lobanov SS, Holtgrewe N, Lin JF, Goncharov AF (2017) Radiative conductivity and abundance of post-perovskite in the lowermost mantle. *Earth and Planetary Science Letters* 479: 43-49, doi: 10.1016/j.epsl.2017.09.016
- Lobanov SS, Geballe ZM (2022) Non-isotropic contraction and expansion of samples in diamond anvil cells: implications for thermal conductivity at the core-mantle boundary. *Geophysical Research Letters* 49: e2022GL100379, doi: 10.1029/2022GL100379
- Mazzucchelli ML, Cordier P, Trepmann C (2026) Carrying the planet on their backs: how minerals respond to stress. *Elements* 22: 96-101
- Mössbauer RL (1958) Kernresonanzfluoreszenz von Gammastrahlung in <sup>191</sup>Ir. *Zeitschrift für Physik* 151: 124-143, doi: 10.1007/BF01344210
- Ohta K and 5 coauthors (2012) Experimental and theoretical evidence for pressure-induced metallization in FeO with rocksalt-type structure. *Physical Review Letters* 108: 026403, doi: 10.1103/PhysRevLett.108.026403
- Ohta K, Wakamatsu T, Kodama M, Kawamura K, Hirai S (2020) Laboratory-based x-ray computed tomography for 3D imaging of samples in a diamond anvil cell *in situ* at high pressures. *Review of Scientific Instruments* 91: 093703, doi: 10.1063/5.0014486
- Ohta K and 5 coauthors (2025) Electrical and thermal conductivities of Fe-Ni-Si alloy under core conditions: a reevaluation. *Physics of the Earth and Planetary Interiors* 363: 107351, doi: 10.1016/j.pepi.2025.107351
- Oka K, Inada M, Okuda Y, Hirose K (2024) Leveraging oxide reactive sputtering for thermal insulation in laser-heated diamond anvil cell. *High Pressure Research* 44: 159-167, doi: 10.1080/08957959.2024.2346171
- Öztürk Ö, Mtingwa SK, Zema M (2026) Shared light, shared science with LAAAMP: expanding participation in mineral physics. *Elements* 22: 121
- Pollack HN, Hurter SJ, Johnson JR (1993) Heat flow from the Earth's interior: analysis of the global data set. *Reviews in Geophysics* 31: 267-280, doi: 10.1029/93RG01249
- Singwi KS, Sjölander A (1960) Resonance absorption of nuclear gamma rays and the dynamics of atomic motions. *Physical Review* 120: 1093-1102, doi: 10.1103/PhysRev.120.1093
- Sinmyo R, Hirose K, Ohishi Y (2019) Melting curve of iron to 290 GPa determined in a resistance-heated diamond-anvil cell. *Earth and Planetary Science Letters* 510: 45-52, doi: 10.1016/j.epsl.2019.01.006
- Solomatova NV, Scheller EL, Trumbo SK (2026) Illuminated worlds: how spectroscopy lights the way in Earth and planetary sciences. *Elements* 22: 82-88
- Stixrude L, Scipioni R, Desjarlais MP (2020) A silicate dynamo in the early Earth. *Nature Communications* 11: 935, doi: 10.1038/s41467-020-14773-4
- Stixrude L (2026) Mark Bukowinski and his legacy in theoretical mineral physics. *Elements* 22: 118-120
- Torchio R and 10 coauthors (2020) Melting curve and phase relations of Fe-Ni alloys: implications for the Earth's core composition. *Geophysical Research Letters* 47: e2020GL088169, doi: 10.1029/2020GL088169
- White TG and 26 coauthors (2025) Superheating gold beyond the predicted entropy catastrophe threshold. *Nature* 643: 950-954, doi: 10.1038/s41586-025-09253-y
- Zhou Y, Dong ZY, Hsieh WP, Goncharov AF, Chen XJ (2022) Thermal conductivity of materials under pressure. *Nature Reviews Physics* 4: 319-335, doi: 10.1038/s42254-022-00423-9 ■

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