Astro2020 Science White Paper

Exoplanets and High Energy Density Plasma Science

Thematic Areas: ☒ Planetary Systems ☒ Star and Planet Formation

☐Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics

☐Stars and Stellar Evolution ☐Resolved Stellar Populations and their Environments

☐Galaxy Evolution ☐Multi-Messenger Astronomy and Astrophysics

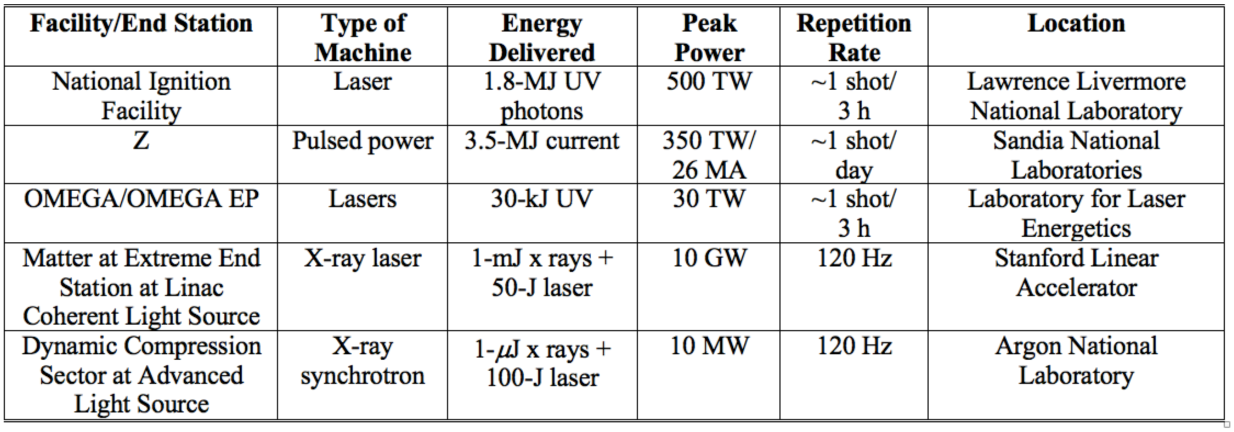
Principal Author:
Name: Adam Frank
Institution: University of Rochester
Email: afrank@pas.rochester.edu
Phone: 585-275-1717

Co-authors: (names and institutions)
Sara Seager (MIT), Miki Nakajima (UR), Adam Burrows (Princeton), Gilbert Collins (UR/LLE), Mohamed Zagoo (UR/LEE), Pierre Gourdain (UR), Eric G. Blackman (UR/LLE), John Tarduno (UR), Adam Sefkow (UR/LLE)

Abstract (optional): Exoplanet science has moved rapidly beyond its initial observational discovery phase with an emerging enterprise of understanding planet formation, evolution, structure and habitability. Understanding conditions in planetary interiors is essential to all of these issues. The evolving state of a planet's deep interior will determine not only bulk physical characteristics like density and radius but also whether dynamo and plate tectonics can occur, both of which may be key to understanding the potential for a rich and detectable biosphere. But understanding planetary interiors depends on understanding matter under extreme pressures. This takes researchers into new regimes of physics which in turn, demand new methods. Material under Megabar pressures represents a frontier domain of plasma physics called Warm Dense Matter (WDM) which has recently become accessible via direct laboratory studies. In this white paper we review the state of exoplanet interior studies and the ability of High Energy Density Plasma (HEDP) WDM techniques to address critical open issues.

Introduction. Exoplanet science has, in the last 20 years, moved rapidly beyond its initial discovery phase. With thousands of worlds confirmed researchers are now exploring the exoplanet census and its implications for key issues like planet formation, evolution, structure and habitability. Understanding conditions in planetary interiors are essential to all of these issues. The evolving state of a planet's deep interior will determine not only the planets gross physical characteristics (like radius) but also determine, for example, if a dynamo is possible and if plate tectonics can occur. These are both issues which may be key to understanding a world's potential for harboring a rich (and therefore detectable) biosphere. But understanding planetary interiors demands an understanding of matter under extreme pressures which takes researchers into new domains of physics which demand new methods to reveal. It is a remarkably fortuitous overlap that just as astrophysical exoplanet observations are demanding new knowledge of matter under Megabar pressures, such phenomena have become accessible via direct laboratory studies. In this white paper we review the state of exoplanet interior studies and the ability of High Energy Density Plasma (HEDP) techniques to address critical open issues

2. Plasmas at Extreme Pressures. How does extreme (atomic-scale) pressure affect the physics of matter and what are its astrophysical implications? Extreme pressure here is defined as being comparable to the atomic (quantum) unit of pressure, which is the pressure required to seriously disrupt the shell structure of atoms. Note that every time scientists explore matter beyond the threshold of an atomic unit, there has been a fundamental shift in science. The discovery of Bragg scattering in 1920, for example brought researchers to direct exploration of sizescales comparable to the Bohr radius (a_0) allowing the development of Crystallogrophy. Reaching atomic transition timescales (h/E_h) in 2001 allowed real-time chemistry to be directly explored. Currently the only unexplored atomic unit is pressure. Exploring matter at atomic pressures (E_h/a_0^3) is necessary because most of the recently discovered extrasolar planets have deep internal pressures at, or beyond, such conditions. The direct exploration of such pressures represents the promise of High Energy Density Plasma (HEDP) science.



Facility/End Station	**Type of Machine**	**Energy Delivered**	**Peak Power**	**Repetition Rate**	**Location**
National Ignition Facility	Laser	1.8-MJ UV photons	500 TW	~1 shot/ 3 h	Lawrence Livermore National Laboratory
Z	Pulsed power	3.5-MJ current	350 TW/ 26 MA	~1 shot/ day	Sandia National Laboratories
OMEGA/OMEGA EP	Lasers	30-kJ UV	30 TW	~1 shot/ 3 h	Laboratory for Laser Energetics
Matter at Extreme End Station at Linac Coherent Light Source	X-ray laser	1-mJ x rays + 50-J laser	10 GW	120 Hz	Stanford Linear Accelerator
Dynamic Compression Sector at Advanced Light Source	X-ray synchrotron	1-μJ x rays + 100-J laser	10 MW	120 Hz	Argon National Laboratory

Figure 1. High Energy Density Plasma Experimental Platforms

Over the last few decades a new generation of experimental capabilities have come on-line (Table 1) making it possible for scientists to explore the extreme pressures and temperatures common to deep interior conditions of planets. At such pressures, quantum mechanics can enter the macro realm, producing a new frontier in physics called Warm Dense Matter (WDM). Early quantitative experiments approaching the WDM regime are rich with discovery. Examples include unexplained chemistry in WDMs,[2,3] the insulator-to-metal transition for many materials that occurs at the onset of disorder,[4–6] the metallization of solid hydrogen,[7] first-order plasma-phase transition,[8] localization and pairing of electrons in ultradense matter,[9–11] ionization potential depression, and general photon transport in hot dense matter that disagree significantly with state-of-the-art calculations.[12,13]

We note that questions about matter at extreme pressures have long been at the forefront of astrophysics. At the end of the 20th century, Van Horn described several fundamental grand challenges to exploring astrophysical plasmas.[14] How do we treat matter when the thermal energy, Fermi energy, and coulomb energy are all comparable, causing a breakdown in traditional approximations? What happens when interatomic distances are less than key quantum-length scales? What is the nature of hot dense plasma when the photon and/or magnetic-field pressures are comparable to material pressure? What are the astrophysical implications of matter at extreme pressures? At the time Van Horn posed these questions, such conditions were inaccessible in the laboratory. As a result, these challenges still limit our fundamental understanding. Today however we can explore these grand challenges at and beyond atomic pressures, including the equation of state (EOS), structure, and transport of planetary and stellar constituents both with and without magnetic fields.

3. Exoplanet Science and HEDP Overview. The remarkably diverse range of masses, total internal energies, and compositions of exoplanets cannot be explained by current physics of planet formation. Planet formation and evolution have moved beyond an era focused on dynamics of accretion followed by secular cooling and have entered a new era where robust coupling between physical processes and material properties at extreme conditions is required. Modeling the formation, evolution, interior structure, and magnetic fields of such a diversity of planets depends fundamentally on the EOS, chemistry, and optical and transport properties of the constituent materials under WDM conditions. Protostellar disk environments and planetary-formation processes determine the elemental composition of a planet. Therefore, while the range of planets found within and outside our solar system all draw from the same collection of chemical elements and possess broadly similar formation scenarios, the effect of pressure and temperature on chemical bonding will likely lead to very different behavior that cannot be predicted from our “low-pressure” chemical intuition alone.[15]

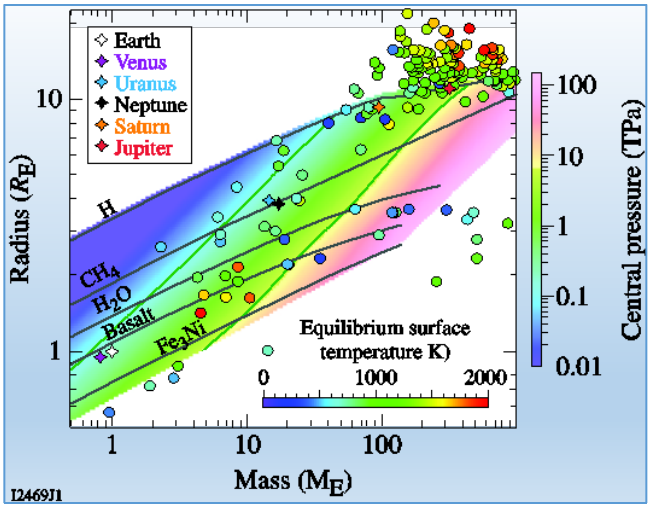


Figure 2 The diversity of exoplanets shown by planet radius versus mass. The background color corresponds to the central pressure for a given mass radius and composition.193 Today’s HED facilities can, for the first time, access and enable key accurate benchmark

For example, once formed, cooling for rocky and/or terrestrial planets is secondary to their structure but is central[16,17] to the radius/mass/age relation of gas giants and ice giants such as Jupiter [1 M_J = 318 Earth masses (= M_E)], Saturn (95 M_E), Uranus (14.5 M_E), and Neptune (17.2 M_E), as well as of the gaseous exoplanets now being discovered.[18] Cooling such giants is contingent upon surface radiative fluxes, which are functions of molecular transitions/emissivity, miscibility, and internal specific heats.[19-20] The latter depend crucially on the material thermodynamics throughout the planet, including its high-pressure core and interior, and the EOS of materials under extreme pressure.

More fundamentally, the thermodynamic connection between pressure, temperature, mass density, and composition, i.e., its EOS, determines a planet's density structure in hydrostatic equilibrium against gravity. Knowledge of the pressure as a function of density and temperature for a given composition and of the specific heat of planetary materials at high pressure is essential for understanding the structure of planets and their evolution.

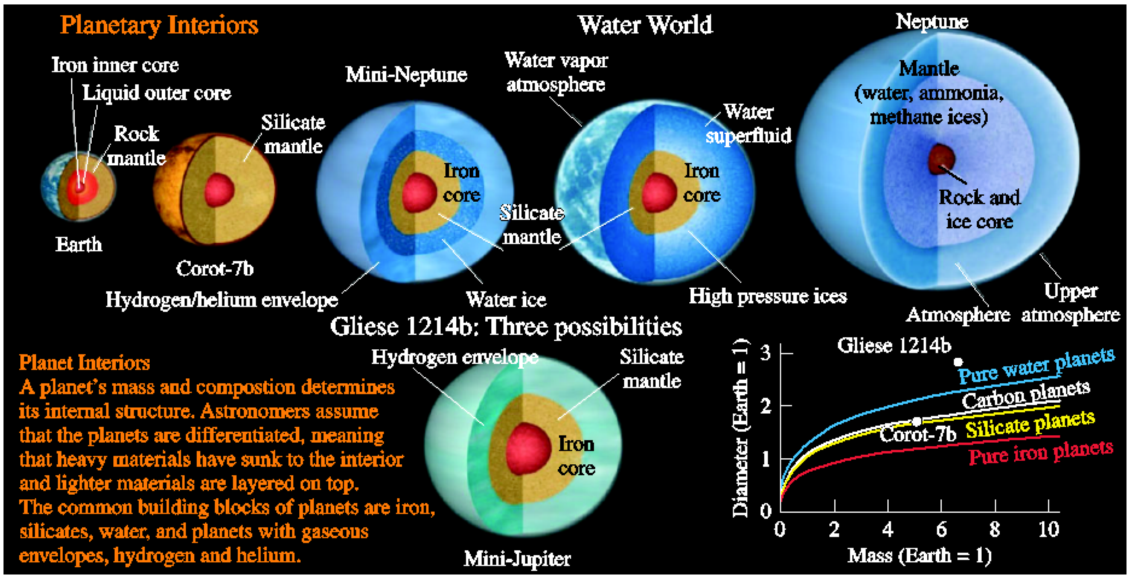
Gas/Ice Giants: HEDP WDM studies of gas giant interiors have rich history but only recently have experimental techniques allowed a deeper and more complete study to become possible. Present uncertainties in the masses and compositions of the cores of the gas giants as well as their central pressures are not precisely known. While central pressure of the Earth is ~0.36 TPa, those of Jupiter can reach up to ~8 TPa. Using dynamic high-pressure measurements via shock driven compression (and other methods) HEDP WDM laboratory studies can reach these pressure domains and provide the keys to understanding gas/ice giant interiors. Materials that can be studied include hydrogen/helium mixtures salted with heavier elements that constitute the envelopes of giants and ice giants; mixtures of ices of oxygen, carbon, and nitrogen that may constitute the cores of giants and the bulk of ice giants.

In addition, of particular relevance to gas-giant evolution, is their specific heat and hydrogen/helium immiscibility curve, all accessible via the theoretical and experimental techniques of HEDP studies. We note also that ongoing and upcoming measurements of the higher gravitational moments of Jupiter and Saturn via the Juno mission[21] and the Cassini Grand Finale,[22] provide planetary density-profile data of unprecedented character. These data, along with high-pressure EOS data and benchmarked theory for planetary materials from HEDP laboratory studies will provide key constraints for new models of solar systems and exoplanets constructed by our team and teams worldwide.

Super-Earths: The rock/iron constituents of super-Earths are also accessible to HEDP WDM methods. This makes the overlap between Super-Earth and HEDP studies particularly strong. Super-Earths in the size range between Earth and Neptune represents the most-abundant population of exoplanets detected to date[23]. Approximately half of Sun-like stars have planets of 1× to 4× the Earth's radii in size (and orbital periods <100 days[24]). These planets have attracted much attention because they have no analogues in our own solar system and, therefore, are crucial to understanding the range and distribution of possible planetary architectures (Fig 3). For this size range, a plethora of planetary types are proposed including iron planets, terrestrial planets (Mercury-like to

Earth-like), water planets (Ganymede-like), coreless planets, lava planets, carbon planets, and sub-Neptunes.[25] Those with larger radii (greater than ~2 Earth radii) appear to be sub-Neptunes, suggesting that even relatively small planets can attract and retain hydrogen-rich envelopes[16]. The central pressures of these worlds range by more than three orders of magnitude and all these pressures are now accessible experimentally.

Exoplanets with radii less than ~1.6 R_E may be composed mainly of heavier elements such as Si, Mg, Fe, and O[26]. For example, $MgSiO_3$ bridgmanite is a major component of terrestrial planet interiors; however, it expected to break down in super-Earth mantles and different dissociation pathways have been proposed.[27] The phase diagrams of oxides, silicates, and metals at ultrahigh P–T conditions can be determined via HEDP studies and therefore can be used to predict the mineralogy and structure of these objects. Recent advances in theoretical and experimental techniques demonstrate the feasibility of such studies,[28,29]



Planet Interiors
A planet's mass and compostion determines its internal structure. Astronomers assume that the planets are differentiated, meaning that heavy materials have sunk to the interior and lighter materials are layered on top. The common building blocks of planets are iron, silicates, water, and planets with gaseous envelopes, hydrogen and helium.

I2471J1

Figure 3. Examples of possible interior structures of terrestrial and extra-solar planets in the size range spanning from Earth to Neptune.[231]

Understanding melting behavior and the properties of liquid silicates and metal alloys at ultrahigh P–T conditions is also needed for super-Earth applications. Heating during accretion and differentiation in the early stages of planetary evolution is likely sufficient to melt the silicate mantle of terrestrial planets, creating magma oceans that could span a wide range of depths. Degassing of such oceans may play a major role in the development of early atmospheres and affect volatile retention in the interior. High internal temperatures leading to partial melting may also occur as a result of compositional layering, rheological properties, or tidal forcing. Preliminary experiments on melting curves and liquid properties from WDM theory[30] and experiment can be extended to a wider range of compositions constraining fundamental properties including temperature, liquid structure, and partitioning behavior at the pressures of 100 to 1000 GPa and beyond.

For solid exoplanets, the interior chemistry is intrinsically linked to interpretation of observations and to models of planet formation and atmospheric processes. The interior structure not only controls the thermal evolution of the interior, but also exerts a strong influence on the surface environment including the nature of the atmosphere, existence of a magnetic field, and tectonic style[32] (Fig. 4). The interior behavior is, therefore, a critical ingredient for determining whether surface conditions are conducive to habitability.

Pinning down the thermal conductivity at 0.1- to 1-TPa pressures is particularly important for understanding the early geomagnetic field and more generally, the early origin of planetary magnetism in Earth-like planets. Paleomagnetic measurements of single crystals from Paleoarchean rocks reveal significant geomagnetic fields 3.45 Gyr ago[33] at times when the higher thermal conductivities would lead to suppression of thermal convection before the inner core supplies additional heat by crystallization. For the high values of thermal conductivity, the crystallizations would occur too late to drive convection in the early Earth; consequently, standard thermal-convection–driven geodynamo paradigms for the magnetic field at early times could not operate. This circumstance has led to considering other sources of convection, such as composition gradients.[34]

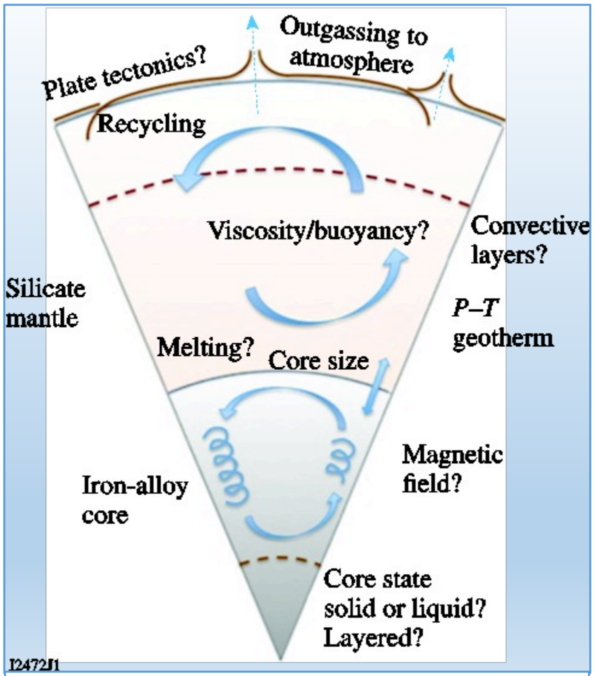


Figure 4 Figure Schematic structure and dynamic behavior of a terrestrial-type super-Earth planet illustrating the key dynamical features that are determined by the planet's mineralogy/chemistry.

Summary: As described above the community finds itself at an exciting moment in exoplanet studies. Reaping the benefits of the wealth of new exoplanet data however will require a new understanding their interiors and this requires a new understanding of matter under extreme pressures (a field called Warm Dense Matter). The development of new High Energy Density Plasma (HEDP) facilities offers a new frontier in the study of WDM in planetary interiors and will likely prove essential in taking us to a deeper view of planets and life in the Universe.

References

1. M. S. T. Bukowinski, “Quantum Geophysics,” Annu. Rev. Earth Planet. Sci. **22**, 167-205 (1994).
2. D. G. Hicks, T. R. Boehly, J. H. Eggert, J. E. Miller, P. M. Celliers, and G. W. Collins, “Dissociation of Liquid Silica at High Pressures and Temperatures,” Phys. Rev. Lett. **97** (2), 025502 (2006).
3. R. S. McWilliams, D. K. Spaulding, J. H. Eggert, P. M. Celliers, D. G. Hicks, R. F. Smith, G. W. Collins, and R. Jeanloz, “Phase Transformations and Metallization of Magnesium Oxide at High Pressure and Temperature,” Science **338** (6112), 1330-1333 (2012).
4. J. Eggert, S. Brygoo, P. Loubeyre, R. S. McWilliams, P. M. Celliers, D. G. Hicks, T. R. Boehly, R. Jeanloz, and G. W. Collins, “Hugoniot Data for Helium in the Ionization Regime,” Phys. Rev. Lett. **100** (12), 124503 (2008).
5. M. Millot, N. Dubrovinskaia, A. Černok, S. Blaha, L. Dubrovinsky, D. G. Braun, P. M. Celliers, G. W. Collins, J. H. Eggert, and R. Jeanloz, “Shock Compression of Stishovite and Melting of Silica at Planetary Interior Conditions,” Science **347** (6220), 418-420 (2015).
6. P. W. Anderson, “Absence of Diffusion in Certain Random Lattices,” Phys. Rev. **109** (5), 1492-1505 (1958).
7. R. P. Dias and I. F. Silvera, “Observation of the Wigner-Huntington Transition to Metallic Hydrogen,” Science 10.1126/science.aal1579 (2017).
8. M. D. Knudson, M. P. Desjarlais, A. Becker, R. W. Lemke, K. R. Cochrane, M. E. Savage, D. E. Bliss, T. R. Mattsson, and R. Redmer, “Direct Observation of an Abrupt Insulator-to-Metal Transition in Dense Liquid Deuterium,” Science **348** (6242), 1455-1460 (2015).
9. J. B. Neaton and N. W. Ashcroft, “Pairing in Dense Lithium,” Nature **400** (6740), 141-144 (1999).
10. J. B. Neaton and N. W. Ashcroft, “On the Constitution of Sodium at Higher Densities,” Phys. Rev. Lett. **86** (13), 2830–2833 (2001).
11. J. Dai, D. Kang, Z. Zhao, Y. Wu, and J. Yuan, “Dynamic Ionic Clusters with Flowing Electron Bubbles from Warm to Hot Dense Iron along the Hugoniot Curve,” Phys. Rev. Lett. **109** (17), 175701 (2012).
12. S. M. Vinko, U. Zastrau, S. Mazevet, J. Andreasson, S. Bajt, T. Burian, J. Chalupsky, H. N. Chapman, J. Cihelka, D. Doria, T. Döppner, S. Düsterer, T. Dzelzainis, R. R. Fäustlin, C. Fortmann, E. Förster, E. Galtier, S. H. Glenzer, S. Göde, G. Gregori, J. Hajdu, V. Hajkova, P. A. Heimann, R. Irsig, L. Juha, M. Jurek, J. Krzywinski, T. Laarmann, H. J. Lee, R. W. Lee, B. Li, K.-H. Meiwes-Broer, J. P. Mithen, B. Nagler, A. J. Nelson, A. Przystawik, R. Redmer, D. Riley, F. Rosmej, R. Sobierajski, F. Tavella, R. Thiele, J. Tiggesbäumker, S. Toleikis, T. Tschentscher, L. Vysin, T. J. Whitcher, S. White, and J. S. Wark, “Electronic Structure of an XUV Photogenerated Solid-Density Aluminum Plasma,” Phys. Rev. Lett. **104** (22), 225001 (2010).
13. J. E. Bailey, T. Nagayama, G. P. Loisel, G. A. Rochau, C. Blancard, J. Colgan, Ph Cosse, G. Faussurier, C. J. Fontes, F. Gilleron, I. Golovkin, S. B. Hansen, C. A. Iglesias, D. P. Kilcrease, J. J. MacFarlane, R. C. Mancini, S. N. Nahar, C. Orban, J. C. Pain, A. K. Pradhan, M. Sherrill, and B. G. Wilson, “A Higher-than-Predicted Measurement of Iron Opacity at Solar Interior Temperatures,” Nature **517** (7532), 56–59 (2015).
14. H. M. Van Horn, “Dense Astrophysical Plasmas,” Science **252** (5004), 384–389 (1991).
15. W. Grochala, R. Hoffmann, J. Feng, and N. W. Ashcroft, “The Chemical Imagination at Work in *Very* Tight Places,” Angew. Chem., Int. Ed. **46** (20), 3620–3642 (2007).

16. D. S. Spiegel and A. Burrows, “Thermal Processes Governing Hot-Jupiter Radii,” The Astrophysical Journal **772** (1), 76 (2013).
17. J. J. Fortney and N. Nettelmann, “The Interior Structure, Composition, and Evolution of Giant Planets,” Space Sci. Rev. **152** (1), 423–447 (2010).
    A. Burrows, M. Marley, W. B. Hubbard, J. I. Lunine, T. Guillot, D. Saumon, R. Freedman, D. Sudarsky, and C. Sharp, “A Nongray Theory of Extrasolar Giant Planets and Brown Dwarfs,” The Astrophysical Journal **491** (2), 856–875 (1997).
18. J. J. Fortney, M. Ikoma, N. Nettelmann, T. Guillot, and M. S. Marley, “Self-Consistent Model Atmospheres and the Cooling of the Solar System’s Giant Planets,” The Astrophysical Journal **729** (1), 32 (2011).
19. J. J. Fortney, R. Helled, N. Nettelmann, D. J. Stevenson, M. S. Marley, W. B. Hubbard, and L. Iess, “The Interior of Saturn,” arXiv:1609.06324v1 [astro-ph.EP] (20 September 2016).
20. S. Finocchiaro and L. Iess, “Numerical Simulations of the Gravity Science Experiment of the Juno Mission to Jupiter,” Adv. Astronaut. Sci. **136** (Part 2), 1417–1426 (2010).
21. L. Spilker and S. Edgington, “Cassini’s Grand Finale: The Final Orbits,” in *European Geosciences Union General Assembly 2016*, Geophysical Research Abstracts (Copernicus Publications, Vienna, Austria, 2016), Vol. 18, p. EGU2016-11198.
22. W. J. Borucki, “KEPLER Mission: Development and Overview,” Rep. Prog. Phys. **79** (3), 036901 (2016).
    A. W. Howard, “Observed Properties of Extrasolar Planets,” Science **340** (6132), 572–576 (2013).
23. T. Duffy, N. Madhusudhan, and K. K. M. Lee, “Mineralogy of Super-Earth Planets,” in *Treatise on Geophysics*, 2nd ed., edited by C. Schubert (Elsevier, Oxford, 2015), Vol. 2, pp. 149–178.
    A. R. Howe, A. Burrows, and W. Verne, “Mass-Radius Relations and Core-Envelope Decompositions of Super-Earths and Sub-Neptunes,” The Astrophysical Journal **787** (2), 173 (2014).
24. H.-B. Niu, A. R. Oganov, X.-Q. Chen, and D. Li, “Prediction of Novel Stable Compounds in the Mg-Si-O System Under Exoplanet Pressures,” Sci. Rep. **5**, 18347 (2015).
25. K. Umemoto and R. M. Wentzcovitch, “Multi-Mbar Phase Transitions in Minerals,” Rev. Mineral. Geochem. **71** (1), 299–314 (2010).
26. F. Coppari, R. F. Smith, J. H. Eggert, J. Wang, J. R. Rygg, A. Lazicki, J. A. Hawreliak, G. W. Collins, and T. S. Duffy, “Experimental Evidence for a Phase Transition in Magnesium Oxide at Exoplanet Pressures,” Nature Geoscience **6** (11), 926–929 (2013).
27. L. Stixrude, “Melting in Super-Earths,” Phil. Trans. R. Soc. A **372** (2014), 20130076 (2014).
28. S. Seager, *Exoplanet Atmospheres: Physical Processes*, Princeton Series in Astrophysics, edited by D. N. Spergel (Princeton University Press, Princeton, NJ, 2010), Chap. 1; C. T. Seagle, E. Cottrell, Y. Fei, D. R. Hummer, and V. B. Prakapenka, “Electrical and Thermal Transport Properties of Iron and Iron-Silicon Alloy at High Pressure,” Geophys. Res. Lett. **40** (20), 5377–5381 (2013).
29. P. J. Tackley, M. Ammann, J. P. Brodholt, D. P. Dobson, and D. Valencia, “Mantle Dynamics in Super-Earths: Post-Perovskite Rheology and Self-Regulation of Viscosity,” Icarus **225** (1), 50–61 (2013).

30. J. A. Tarduno, R. D. Cottrell, M. K. Watkeys, A. Hofmann, P. V. Doubrovine, E. E. Mamajek, D. Liu, D. G. Sibeck, L. P. Neukirch, and Y. Usui, “Geodynamo, Solar Wind, and Magnetopause 3.4 to 3.45 Billion Years Ago,” Science **327** (5970), 1238–1240 (2010).

31. J. G. O’Rourke and D. J. Stevenson, “Powering Earth’s Dynamo with Magnesium Precipitation from the Core,” Nature **529** (7586), 387–389 (2016).