PLANETARY SCIENCE

Molten iron in Earth-like exoplanet cores

Iron crystallization in super-Earth interiors plays a key role in their habitability

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Earth, the only known habitable planet in the universe, has a magnetic field that shields organic lifeforms from harmful radiation coming from the sun and beyond. This magnetic field is generated by the churning of molten iron in its outer core. The habitability of planets orbiting other stars (exoplanets) could be gleaned through better understanding of their iron cores and magnetic fields (*1*). However, extreme pressure and temperature conditions inside exoplanets that are much heavier than Earth may mean that their cores behave differently. On page XXX of this issue, Kraus et al. (*2*) used a powerful laser to generate conditions similar to those inside the cores of such "super-Earths" and reveal that even under extreme conditions, molten iron can crystalize similarly to that found at the base of Earth's outer core.

To date, more than 4500 exoplanets have been discovered, with approximately one-third of them categorized as Earth-like exoplanets (*3*). The discoveries of these exoplanets have raised hopes about finding habitable conditions beyond the solar system, and that exoplanetary habitability could be quite diverse in the universe. Although surface water in a star's habitable zone has always been used as a qualifying condition for habitability, other key factors for habitability lie beneath the surface of the exoplanet, such as the property of its dynamo (the self-sustaining mechanism that generates the magnetic field) (*4*).

Similar to Earth, super-Earths are thought to have formed through collisions and then differentiated into light silicate mantles and heavy iron cores. The iron cores were initially hot and molten, but slowly lost heat to the silicate mantles. If core cooling is efficient, it can lead to iron crystallization. The cooling and solidification processes are thought to be the main sources of power that drives the convection of molten iron in the liquid core, generating magnetic fields through dynamo action (magnetospheres). The pressure-temperature condition where convection occurs is close to adiabatic, meaning that hot upwelling fluid follows a predictable temperature profile without heat gain or loss to the surroundings. Depending on the intersection relation between the iron melting temperature and the adiabatic profile under compression in a super-Earth's core, the molten cores crystalize in two possible scenarios: either in an Earth-like "bottom-up" iron crystallization scenario or in an iron snowflake-like "top-down" scenario (see the figure). Bottom-up crystallization happens in the case of an iron melting curve steeper than adiabatic profile, which is expected to be very efficient in powering and sustaining a dynamo, whereas core dynamos driven by an iron snowflake-like regime may be more difficult to maintain over a long period (*5*). Experimental determination of the crystallization scenarios in super-Earth's cores are thus critical in assessing their magnetic fields and habitability.

Previous laboratory techniques have been limited to relatively low pressure-temperature ranges so that extrapolation to super-Earth cores and theoretical predictions were used in existing models (*6*). Kraus et al. used a laser to mimic the high pressure-temperature conditions and monitored iron crystallization up to ~1000 GPa, and concluded that the Earth-like "bottom-up" scenario is the more likely outcome for super-Earth cores with iron-rich Earth-like compositions. This crystallization can promote the convection of molten iron to generate magnetic fields surrounding super-Earths more readily than previously thought.

Iron in Earth's core is under extreme pressures ranging from 136-360 GPa and temperatures from 4000-6000 K. The melting curve of iron was previously determined up to ~300 GPa using static and dynamic compression techniques (*7-9*). The advance of ultrahigh-power lasers (e.g., the National Ignition Facility) allows scientists to create much higher pressure and temperature conditions. Controlling the duration of the laser power allowed Kraus et al. to generate higher pressures and moderate temperatures to reproduce iron melting and crystallization processes at super-Earth core conditions.

The melting curve of iron up to ~1000 GPa determined by Kraus et al. indicates a melting slope steeper than the expected adiabat in a super-Earth's core. For a super-Earth with ~1.5 times the radius and ~5 times the mass of Earth, the melting temperature at its topmost outer core is estimated to be ~8500 K at ~600 GPa (*2*). Considering a silicate mantle temperature of ~5000 K at its bottom (*10*), a big temperature gradient across the super-Earth's core-mantle boundary could be expected. Therefore, a large heat flow and thermal energy source are responsible for powering its molten iron convection (*11*). As the super-Earth cools, its adiabat first intersects the melting curve of iron at its center, resulting in a bottom-up core solidification. This is the same crystallization scenario happening in Earth.

The thermochemical and gravitational energy provided by these processes can sustain convection and dynamo within super-Earths for billions of years (*12*). By contrast, the iron snowflake-like scenario can occur in the cores of planets and exoplanets with possible substantial amounts of light element(s) that would lower its melting curve. In the snowflake-like scenario, a cooling planet's adiabat intersects the iron melting curve near the top-middle of the core, leading to iron crystals forming and sinking toward its center. This scenario has been proposed to occur inside Mars because of its lower melting temperature caused by the presence of lighter element(s) in its core (*5, 13*).

When exoplanetary cores form, a certain amount of light elements, such as hydrogen, carbon, silicon, oxygen, and sulfur, make their way into the molten core (*14*). Their presence can depress the melting curve, influence the crystal structure stability of iron, and affect the output of thermochemical energy inside the core. Future experimental investigations of light element effects need to be taken into consideration in evaluating the dynamics of exoplanets at extreme conditions. Future investigation of the thermodynamic, transport, and rheological properties of silicate mantles and iron alloys at relevant super-Earth conditions can help better understand core dynamics, Earth-like mantle convection, and, potentially, plate tectonics. Detections of planetary magnetic

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fields outside of Earth's solar system can be combined with laboratory measurements to infer exoplanetary interior processes and habitability.

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