Strange new worlds define new planetary-materials challenges

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Among exoplanets, true Earth twins are hard to characterize, but there are other worlds, "Earth cousins" - a little bigger or a little hotter - that we can still use to understand planetary habitability. More lab and numerical experiments are needed to make the most of this opportunity.

Are the processes that generate habitability in our Solar System common or rare? Answering this question by observing Earth-analog exoplanets (Earth-sized planets in the Habitable Zone, HZ) poses an enormous challenge, and the signal/noise will be marginal even with next generation telescopes. It will be much easier to close the loop between hypothesis and observational test for "Earth cousins" - small-radius exoplanets that lack solar system analogs, but are more observationally accessible (Fig. 1).

For exoplanets, the observable is the atmosphere. Atmospheres are now routinely characterized for Jupiter-sized exoplanets (e.g. Zhang 2020). Constraints are now being acquired (e.g. Benneke et al. 2019, Kreidberg et al. 2019) for atmospheric properties of smaller worlds (radius R less than 3.5 Earth radii, $R_{\oplus}$), which are very abundant. More information will be revealed by near-future observatories such as James Webb Space Telescope (JWST) and next-generation large aperture ground-based telescopes, applying both existing methods and new techniques such as High-Resolution Cross-Correlation Spectroscopy (HRCCS). For these smaller worlds (as for Earth), the key to understanding atmospheric composition is atmosphere-interior exchange during planet formation and evolution. For many of these small exoplanets, atmosphere-interior exchange occurs at volatile-silicate interfaces that have pressure/temperature/composition ($P/T/X$) regimes that are little-explored by laboratory and numerical experiments (Fig. 1b). To use exoplanet atmosphere data to interpret the origin and evolution of these strange new worlds, we need new planetary materials experiments.

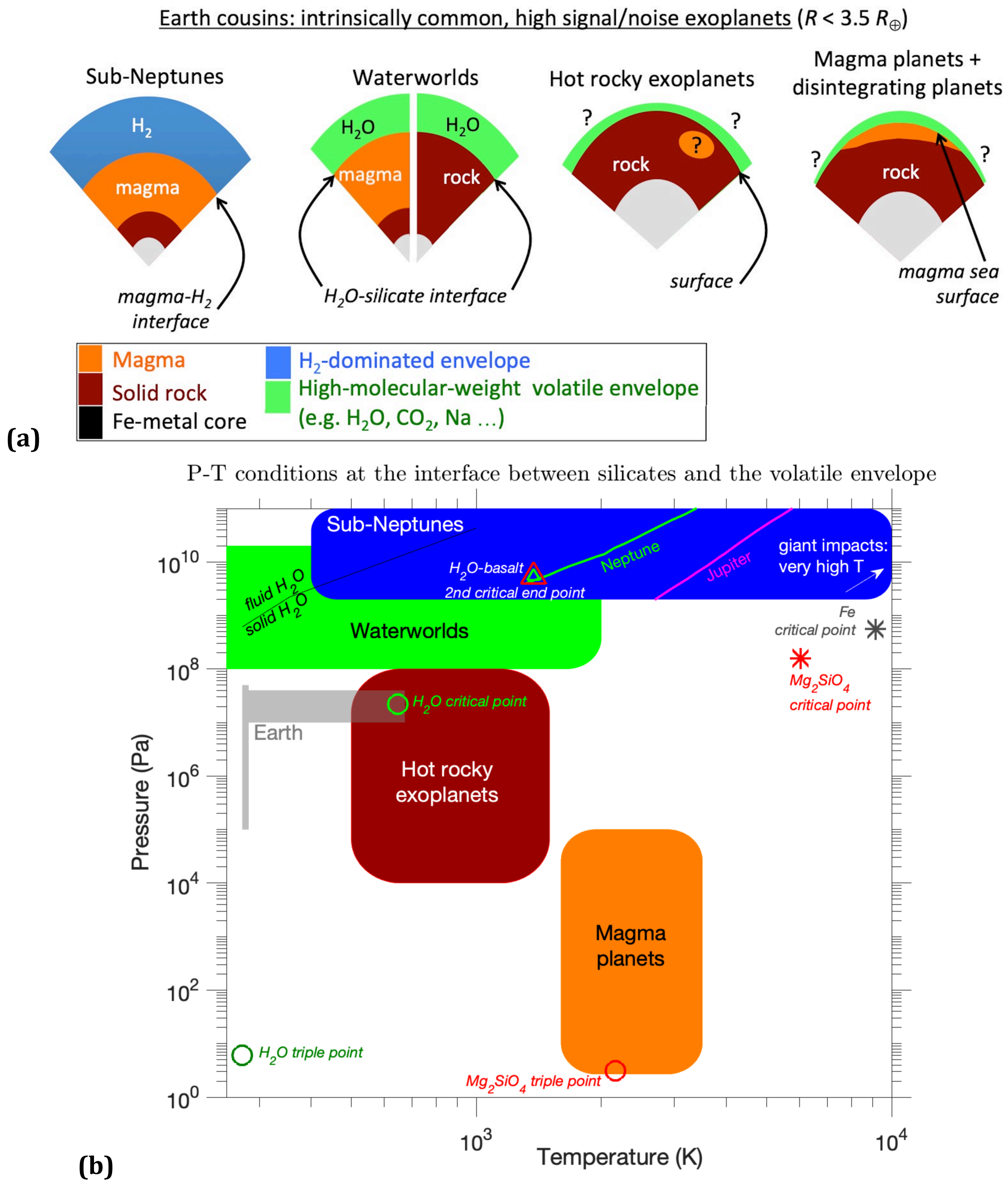

Fig. 1. **(a)** Four intrinsically common, high signal/noise exoplanet classes that have no Solar System analog, with hypothetical cross-sections showing interfaces that can be investigated using new laboratory and numerical experiments. **(b)** *P-T* diagram showing *P-T* conditions at the volatile-silicate interface on these worlds.

Here we discuss four new classes of planet, and planetary materials investigations needed to understand them. Understanding these worlds will help us understand planets in general, and Earth-like worlds in particular. For example, "Earth cousin" exoplanets can probe the delivery and distribution of life-essential volatile elements. Fundamental to habitability is the abundance of life-essential volatile elements (e.g. C) interior to the Habitable Zone, because that probes volatile delivery and loss processes that operate within the HZ. For example, rocky planets now in red dwarf HZs spend >10^8 yr inside the runaway greenhouse limit - suggesting a long-lived magma ocean phase. Whether these worlds are habitable today will depend on the amount of life-essential volatile elements supplied from greater distances from the star (e.g. Tian & Ida 2015) as well as their retention during and after the magma ocean phase. But volatiles are a small fraction of a rocky planet's mass, so quantifying volatile abundance is hard. Earth cousins offer several natural solutions that make volatiles easy to detect (Fig. 1a): disperse the volatiles (disintegrating rocky planets); bake out the volatiles and drive them to the surface, while heating and thus puffing-up the atmosphere (making spectral features more visible) (hot rocky exoplanets); or stretch out the volatiles (by mixing them into low-molecular-weight sub-Neptune atmospheres, increasing atmosphere scale height).

Sub-Neptunes: ~10^3 confirmed - Sub-Neptunes (radius 1.6-3.5 $R_\oplus$), which are statistically about as common as stars, blur the boundary between terrestrial planets and gas giants. Strong (though indirect) evidence indicates that the known sub-Neptunes are mostly magma by mass, and mostly atmosphere by volume (e.g. Bean et al. 2020). This defines an interface at 10-100 kbar between magma and the H_2-dominated atmosphere. Interactions at this interface dictate the chemistry and puffiness of the atmosphere (e.g. Kite et al. 2020). For example, H_2O, other volatiles, and other components can become significant fractions of the vapor, leading to chemically more complex atmospheres.

To quantify the solubilities of gases and gas mixtures in realistic magma ocean compositions (and in iron alloy) and at a wider range of pressure than we now have, and the equation-of-state and Prandtl number and chemical kinetics of H_2-magma mixtures, we need molecular dynamics calculations backed up by laboratory checks (e.g., Diamond Anvil Cell). To understand the extent of mixing between H_2, silicates, and metal during sub-Neptune assembly and evolution, we need more impact simulations (e.g. Davies et al. 2020), and an improved understanding of double-diffusive convection (e.g. Garaud 2018). Within this *P-T-X* regime full miscibility between silicates and molecular hydrogen becomes important. Both the atmosphere and the magma might generate magnetic fields. Because sub-Neptunes are so numerous, we cannot understand the exoplanet mass-radius relation (in effect, the equation-of-state of planets in the Galaxy) without understanding H_2-magma interaction on sub-Neptunes.

Waterworlds: Hundreds of candidates – Earth's water mass fraction is $\sim 10^{-4}$, in contrast to Europa, Ceres, and the carbonaceous chondrite parent bodies, which have (50 – 3000)× greater H_2O mass fraction. Theory predicts that such H_2O-rich worlds will be common in Habitable Zones (HZs) (e.g., Izidoro et al. 2014), and even closer to the star. JWST will have the power to confirm or refute this theory (Greene et al. 2016). Descending through the volatile-rich outer envelope of a waterworld, we might find habitable temperatures at shallow depths (Kite & Ford 2018), but at 10 kbar or more encounter silicate-volatile interfaces featuring supercritical fluids (e.g. Nisr et al. 2020), potentially with full miscibility of H_2O and silicates (Ni et al. 2017). What are the gas production / uptake equilibria and rates for rock-volatile interfaces at waterworld "seafloors"? Can they sustain a habitable climate? With no land, can seafloor reactions supply nutrients? Will tectonics and volcanism be suppressed by high pressures and stratification? As for the deep interiors of Titan and Ganymede in our own solar system, key open questions include the role of clathrates (e.g. Ramirez & Levi 2018), and salt(s) solubility and transport through high-pressure ice layers. Some habitable water layers may be cloaked beneath H_2 (Madhusudhan et al. 2020). More laboratory experiments are needed to understand processes at waterworld seafloors. Indeed, this is the *P*-*T* domain of metamorphic petrology, and exoplanetary studies would benefit from this expertise. We should expect exotic petrology, especially if these worlds are as Na-rich as meteorites. This would also open new paths of research into exotic thermochemical environments.

Hot rocky exoplanets: ~10^3 confirmed. Most stars are orbited by a radius $\sim 1\ R_\oplus$ to 1.6 $R_\oplus$ (Super-Earth sized) planet that is irradiated more strongly than our Sun's innermost planet (Mercury). These worlds experience high fluxes of atmosphere-stripping photons and stellar wind, although whether or not they retain N/C/S is unknown. For these hot rocky exoplanets (as for Venus?), atmosphere-rock (or atmosphere-magma?) interactions at temperatures too high for liquid water will be important in determining atmospheric composition and survival. But these interactions have been little-investigated (Zolotov 2018). Moreover, vaporization experiments are needed to see if moderately volatile elements are lost fast enough to reset surface spectra, and form a comet-like lag. Many metamorphic and also melting reactions between H_2O and silicate in the range of kPa to 10 GPa are known experimentally or are tractable from thermodynamic models. The less understood parts may arise in planets that have silicate components with different proportions from terrestrial, such that exotic phases become important.

Magma planets (~100 confirmed) and disintegrating planets (~10 confirmed) - Many rocky exoplanets are so close to their star that they have surface seas of almost inviscid magma. For these long-lived seas, chemical evolution is affected by fractionating vaporization (e.g.

Léger et al. 2011, Norris & Wood 2017), and perhaps by exchange with underlying solid rock. After correction for contributions from thermal radiation, magma planets usually have low albedos, but are sometimes highly reflective, perhaps because some surfaces are distilled to Ca/Al-rich ceramic. One magma planet shows factor-of-2 thermal variability from month-to-month (Demory et al. 2016), a global energy balance change >10^4 times greater than anthropogenic climate change on Earth, suggesting fast magma ocean-atmosphere feedbacks. To study magma seas, we need experiments similar to those used to study early stage planet formation: silicate vaporization and kinetics data at 1500-3000 K and 10^{-5} - 100 bars. Exoplanets and exo-planetesimals that stray too close to their star are destroyed. This gives geoscientists a direct view of exoplanetary silicates: the debris tails can be 10^6 km long (van Lieshout & Rappaport 2018). For disintegrating planets that orbit white dwarfs, the debris can form a gas disk whose composition can be reconstructed (e.g., Doyle et al. 2019). To better read the signals from time-variable disintegration, we need a better understanding of condensation/nucleation within the outflow, as well as fractionation processes at and above the disintegrating-planet surface that may cause the observed composition to diverge from the bulk-planet composition.

The study of "Earth cousins" can illuminate the processes underpinning habitability in our Galaxy. By studying Earth cousins, we can learn a lot that is relevant for understanding Earth twins. For example, from sub-Neptunes we can learn about volatile delivery; from water worlds we can learn about the potential habitability of exotic environments, from hot rocky planets we can learn about atmosphere/interior exchange and atmospheric loss, and from disintegrating planets we can learn about the interior composition of rocky bodies. Practically, the laboratory study of processes within these worlds will require repurposing and enhancement of existing facilities rather than entire new facilities. In that sense, the scientific rewards are low-hanging fruit.

Acknowledgements: Thanks to the organizers of the AGU-AAS/Kavli workshop (2019.)

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