

Venus as an Exoplanet Laboratory: Testing the Boundaries of Habitability

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Abstract: The prime focus of astrobiology research is the search for life elsewhere in the universe, and this proceeds with the pragmatic methodology of looking for water and Earth-like conditions. In our solar system, Venus is the most Earth-like planet, yet at some point in planetary history there was a bifurcation between the two: Earth has been continually habitable since the end-Hadean, whereas Venus became uninhabitable. Indeed, Venus is the type-planet for a world that has transitioned from habitable and Earth-like conditions through the inner edge of the Habitable Zone (HZ); thus it provides a natural laboratory to study the evolution of habitability (Way et al. 2016, 2020). At the present time, exoplanet detection methods are increasingly sensitive to terrestrial planets, resulting in a much needed collaboration between the exoplanetary science and planetary science communities to leverage the terrestrial body data within the solar system. In fact, the dependence of exoplanetary science on solar system studies runs deep, and influences all aspects of exoplanetary data, from orbits and formation, to atmospheres and interiors. A critical aspect of exoplanetary science to keep in mind is that, unlike the solar system, we will never obtain in situ data for exoplanet surface environments and thus exoplanet environments may only be inferred indirectly from other measurables, such as planetary mass, radius, orbital information, and atmospheric composition. The inference of those environments in turn are derived from detailed models constructed using the direct measurables obtained from observations of and missions to solar system bodies (Fuji et al. 2014; Madden & Kaltenegger 2018). Thus, whilst ever we struggle to understand the fundamental properties of terrestrial objects within the solar system, the task of characterizing the surface environments of Earth-sized planets around other stars will remain proportionally inaccessible. If we seek to understand habitability, proper understanding of the boundaries of the HZ are necessary, exploring both habitable and

uninhabitable environments. Furthermore, current and near-future exoplanet detection missions are biased towards close-in planets, so the most suitable targets for the James Webb Space Telescope (JWST) are more likely to be Venus-like planets than Earth-like planets (Kane et al. 2014). The further study and understanding of the evolution of Venus' atmosphere and its present state provides a unique opportunity to complement the interpretation of these exoplanet observations (Kane et al. 2018).

Here we describe how the current limitations in our knowledge of Venus are impacting present and future exoplanetary science, including remote sensing techniques that are being or will be employed in the search for and characterization of exoplanets. We discuss Venus in the context of defining the boundaries of habitability, and how candidates from the *Kepler* and *TESS* exoplanet missions are enabling tests of potential runaway greenhouse regimes where Venus analogs may reside. We discuss specific outstanding questions regarding the Venus environment and the relevance of those issues to understanding the atmospheres and interior structure of exoplanets (Kane et al. 2019, 2021).

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