Testing the Boundaries of Planetary Habitability: The Critical Need For In-Situ Data.

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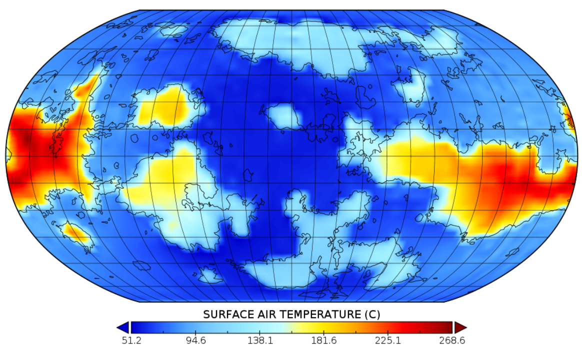
Introduction: The prime focus of astrobiology research is the search for life elsewhere in the universe, and this proceeds with the pragmatic methodology of looking for water and Earth-like conditions. In our solar system, Venus is the most Earth-like planet, yet at some point in planetary history there 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).

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 exoplanets 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).

The Exoplanet Connection: 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).

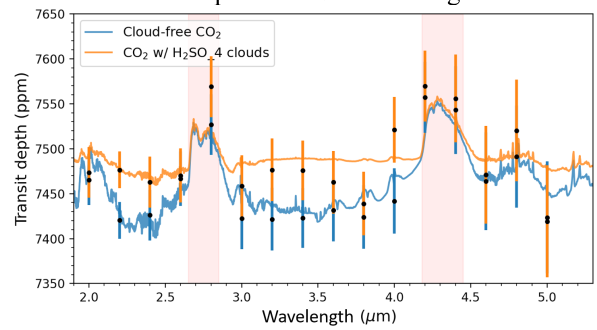
An ExoVenus Catalog: The methodology for this project includes the major processes of Venus data collection and interpretation, connection to exoplanet data from past and current missions, modeling of potential exoVenus atmospheres and interiors, and application to habitability science and mission design. The project draws upon a variety of Venus data sources, including Venera orbiter/lander missions, Pioneer-Venus, Magellan, and Akatsuki, which are being used to create a revised suite of concurrent Venus/Earth geologic and atmospheric timelines. We are also adapting these data to revise boundaries of the Venus Zone (Kane et al. 2014) to incorporate exoplanet discoveries, particularly those from Kepler and the Transiting Exoplanet Survey Satellite (TESS), for which planetary radii have been measured. These are forming the basis of an ExoVenus catalog that will be used to prioritize follow-up observations and determine the occurrence rates of potential post-runaway greenhouse terrestrial environments.

Climate and Interior Models: We adopt the ROCKE-3D atmospheric model (Way et al. 2017) to assess the possible climate states of the top-priority targets from our ExoVenus catalog. ROCKE-3D is capable of exoplanet research via its ability to simulate non-modern Earth atmospheric compositions, pressures, and non-solar incident radiation via an alternative radiation scheme that can be used to create mock disk-integrated spectra, light curves, and transmission spectra that simulate remotely-sensed exoplanet data. An example output from a ROCKE-3D run is shown below, which is the exoVenus candidate Kepler-1649b, based on a variety of properties, such as planet size and insolation flux (Angelo et al. 2017). The simulations demonstrated a rapid divergence from initial temperate conditions toward a moist and subsequent runaway greenhouse environment (Kane et al. 2018). These climate models are produced the first detailed and systematic climate analysis of potential Venus analogs, providing the basis for testing inner boundaries of the HZ.



Our work also includes inferences of possible interior models to constrain the evolutionary history of the planet. The interior structure and mineralogy of a planet is dependent on its total size, thermal state, and bulk composition (Dorn et al. 2015; Unterborn et al. 2018). We are using the ExoPlex tool base to construct planetary phase diagrams, adopting the measured planetary properties and rocky planet-building elements (e.g., Mg, Fe, Si) available from stellar abundances (Hinkel et al. 2014). These models are being added to our catalog of Venus analogs across a broad range of sizes and compositions.

Boundaries of Habitability: Identifying potential Venus analogs could provide us, for the first time, an observational verification of the HZ and its limits predicted by both 1-D and 3-D climate models. Therefore, it is critical to assess the nature of Venus analogs through atmospheric characterization, not only for the purpose of comparison with solar system planets, but also to assess the nature of HZ planets. Furthermore, discovering Venus analogs will also enable us to answer one of the most important questions for habitability: where (or what) is the inner edge of HZ? Our project uses the diversity of exoplanet properties to assess runaway greenhouse conditions as a function of planet mass, size, compositional inventory, outgassing, and atmospheric evolution. The below figure is an example of our exoVenus catalog holdings; a predicted spectrum for the exoVenus candidate, TRAPPIST-1c. It is simulations such as these that will provide the backbone for target selection planning toward the characterization of potential Venus analogs.



In-situ Data Requirements: The development of our exoVenus targets and spectra rely upon the known atmospheric chemistry, temperature-pressure profile, and habitability history of Venus. Thus our work will identify key Venus properties that require significantly improved measurements, from which the deficiencies in our simulated data will substantially benefit. The planned data acquisition by DAVINCI, EnVision, and VERITAS, are being incorporated into our models to test the expected impact of these missions on the characterization of Venus analogs, and our understanding of how the boundaries of habitability are determined and evolve with time.

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