Venus as an Anchor Point for Planetary Habitability. Stephen R. Kane[1] and Paul K. Byrne[2], [1]*University of California, Riverside, CA, USA*, [2]*Washington University in St. Louis, St. Louis, MO, USA.*

Introduction: The topic of terrestrial planetary habitability is one of the most active, exciting, yet challenging areas of active planetary and space science research. The importance of the topic largely relates to the astrobiological implications of understanding the sustainability of temperate surface conditions on large, rocky planets but is also relevant to, for instance, forecasting Earth's future climate progression.

The presence of surface liquid water throughout most of Earth's history in particular is deemed as having played a crucial role in the origin and development of life on our planet, and may be a necessary—if on its own likely insufficient—requirement for similar biological processes elsewhere. Temperate surface conditions may have been present for a time on other rocky bodies before being truncated by planetary properties and/or environmental conditions, as in the case of Mars. Timescales that allow advanced biochemistry to emerge may require a relatively narrow range of planetary and stellar properties, and the primary objective of planetary habitability studies is thus to identify and quantify the boundaries of such parameters. Moreover, the predictive capabilities of a systems-based planetary science approach, accounting for interactions between interiors, atmospheres, and external factors, is crucial for inferring potentially habitable environments in the context of terrestrial exoplanet characterization.

The recent National Academies' decadal surveys for astronomy and astrophysics [1] and for planetary science and astrobiology [2] both prioritize the understanding of habitable environments as a key research topic for the coming decades. The study of Venus, establishing its evolutionary pathway with respect to Earth, and recognizing potential Venus surface environments inferred from exoplanet upper atmospheric spectra will together form essential components of fulfilling this high, cross-disciplinary science priority. Here, we discuss the study of Venus in the context of these decadal surveys' recommendations, and the required steps for realizing the goals of using Venus as a planetary habitability anchor point.

Venus–Earth Divergence: Planetary habitability is a foundational space science topic because identifying and understanding the factors that influence planetary surface conditions is essential for assessing whether other bodies might once have or do today host conditions amenable to life. In terms of bulk properties, Venus and Earth are remarkably similar: they are very close in size, and the mass of Venus is around 80% that of Earth. Yet there are major differences between the two planets, too. For example, the insolation at Venus is almost twice that of Earth; its solid-body (retrograde) rotational period is 243 days; and the Venus atmosphere is almost entirely CO_2 (with a small amount of N_2 and trace abundances of other gasses such as SO_2, Ar, and water vapor). Moreover, the planet is cloaked in a global layer of H_2SO_4 clouds, which help give the planet a Bond albedo more than twice that of Earth. Together, the atmosphere's physical and chemical properties render the surface hotter than a self-cleaning oven with a pressure about that of 900 m underwater on Earth. Clearly, there has been a major divergence in the evolutionary pathways of Venus and Earth, and assessing the relative contributions of the many differences between these sibling planets is key to understanding planetary habitability for large rocky worlds in general.

Given our lack of knowledge regarding Venus, there are several evolutionary pathways for Venus that are consistent with the present data, including those in which Venus was previously habitable [3]. **Figure 1** summarizes some of the factors that govern habitability factors and the extent to which they have been measured for Venus and Earth. Although we lack the ability with presently available data to establish which model for Venus' evolution is correct, there are intrinsic properties of the planet we *can* measure that would enable us to definitively answer this question. For example, assaying the noble gas elemental and isotopic compositions of the Venus atmosphere would place vital constraints on models of the planet's initial volatile inventory and its history of water loss [4,5]—the very focus of a strategic research activity in Q.4 "Impacts and Dynamics" in the planetary science decadal (pg. 6-22) [2].

The Exoplanet Connection: Present exoplanet detection techniques 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 for the Solar System, we will functionally 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 are, in turn, derived from detailed models constructed using the direct measurables obtained from observations of and missions to Solar System bodies [6,7].

Thus, although ever we struggle to understand the fundamental properties of terrestrial objects within our own planetary system, the task of characterizing the surface environments of Earth-sized worlds around other stars will remain proportionally inaccessible. If we seek to understand the habitability of such bodies fully, we must characterize those factors that influence uninhabitable conditions as well, such as the spatial and temporal extent of the so-called "habitable zone." Furthermore, current and near-future exoplanet detection missions are biased towards close-in planets, so the most suitable targets for telescopes such as JWST are more likely to be Venus-like planets than Earth-like planets [8]. 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 [9]—also serving to place the evolution of the second planet's atmosphere within a broader exoplanet context.

The Path Forward: Fully understanding how a terrestrial planet becomes habitable and remains so is a fundamental challenge for the planetary science and astrobiology community, given the diversity and complexity of intrinsic and extrinsic processes that contribute to sustain habitable conditions over geological and biological time scales. In the face of this challenge, it is imperative that the full range of terrestrial planet atmospheric evolution data within the Solar System be exploited. Although Venus represents a clear end-member of planetary habitability, its contributions to understanding the prevalence of long-term temperate surface conditions on large rocky worlds have yet to be fully realized. Upcoming missions to Venus, including NASA's VERITAS and DAVINCI, and ESA's EnVision spacecraft, will begin to flesh out this understanding. We advocate for, and in this presentation will discuss, how the recent decadal surveys present a united front toward this goal by calling on the community to learn everything we can about Venus' evolutionary history.

References: [1] National Academies of Sciences, Engineering, and Medicine (2023) *Pathways to Discovery in Astronomy and Astrophysics for the 2020s*. Washington, DC: NAP [2] National Academies of Sciences, Engineering, and Medicine (2023) *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032*. Washington, DC: NAP. [3] Way, M. J. et al. (2016) *Geophys. Res. Lett.*, *43*, 8376. [4] Gillmann, C. et al. (2009) *Earth Planet. Sci. Lett.*, 286, 503–513. [5] Kane, S. R. et al. (2019) *JGR Planets*, *124*, 2015–2028. [6] Fuji, Y. et al (2014) *Astrobiology*, *14*, 753–768. [7] Madden, J. H. & Kaltenegger, L. (2018) *Astrobiology*, *18*, 1559–1573. [8] Kane, S. R. et al. (2014) *Astrophys. J. Lett.*, *794*, L5. [9] Kane, S. R. et al (2018) *Astrophys. J.*, *869*, 46.

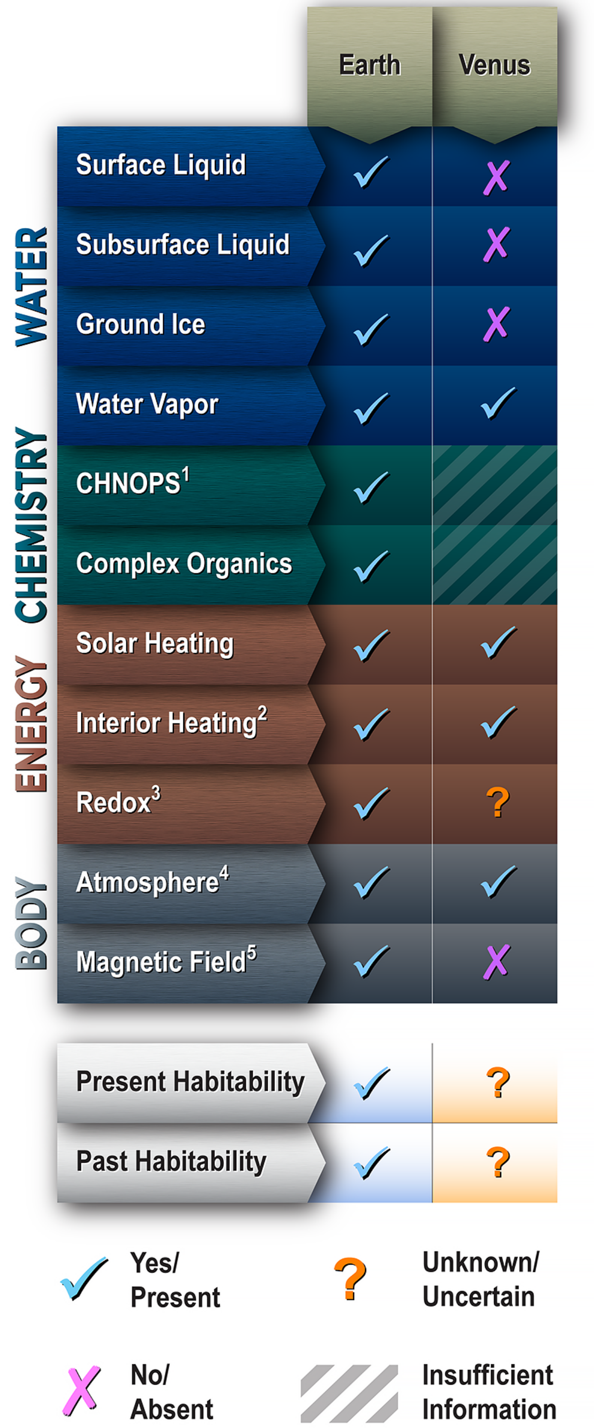

Figure 1. The extent to which factors that govern planetary habitability are present for Earth and Venus. [1]The life-supporting elements C, H, N, O, P, or S (not all need be present); [2]Interior heating derived from accretion, differentiation, radiogenic decay, and/or tidal dissipation; [3]The prospect for any element or molecule to be reduced or oxidized as a source of chemical energy for life; [4]Substantial atmospheres only; [5]Intrinsically generated magnetic fields only. Adapted from [2].