VENUS AS AN EXOPLANETARY LABORATORY: TESTING THE BOUNDARIES OF HABITABILITY

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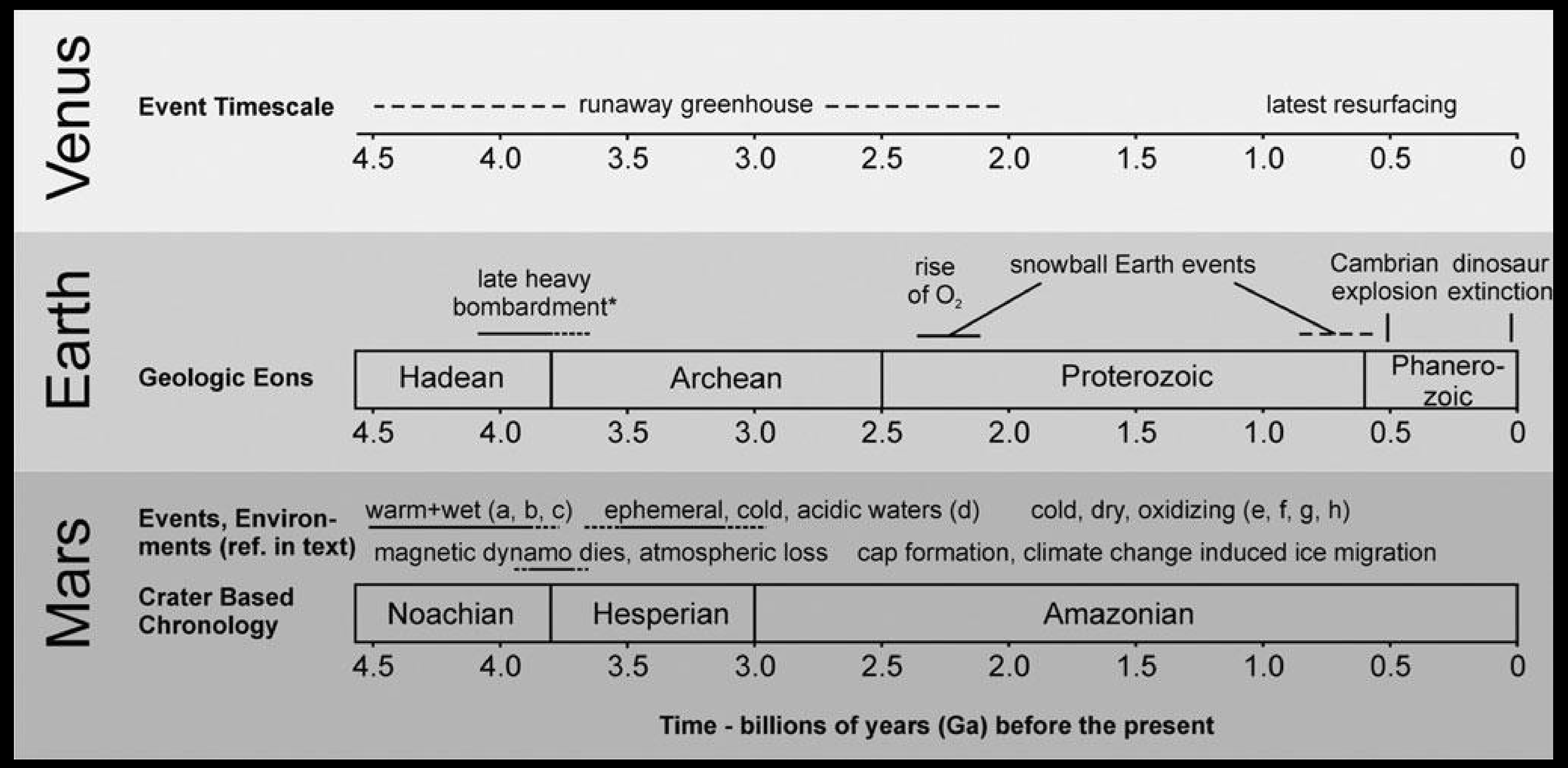
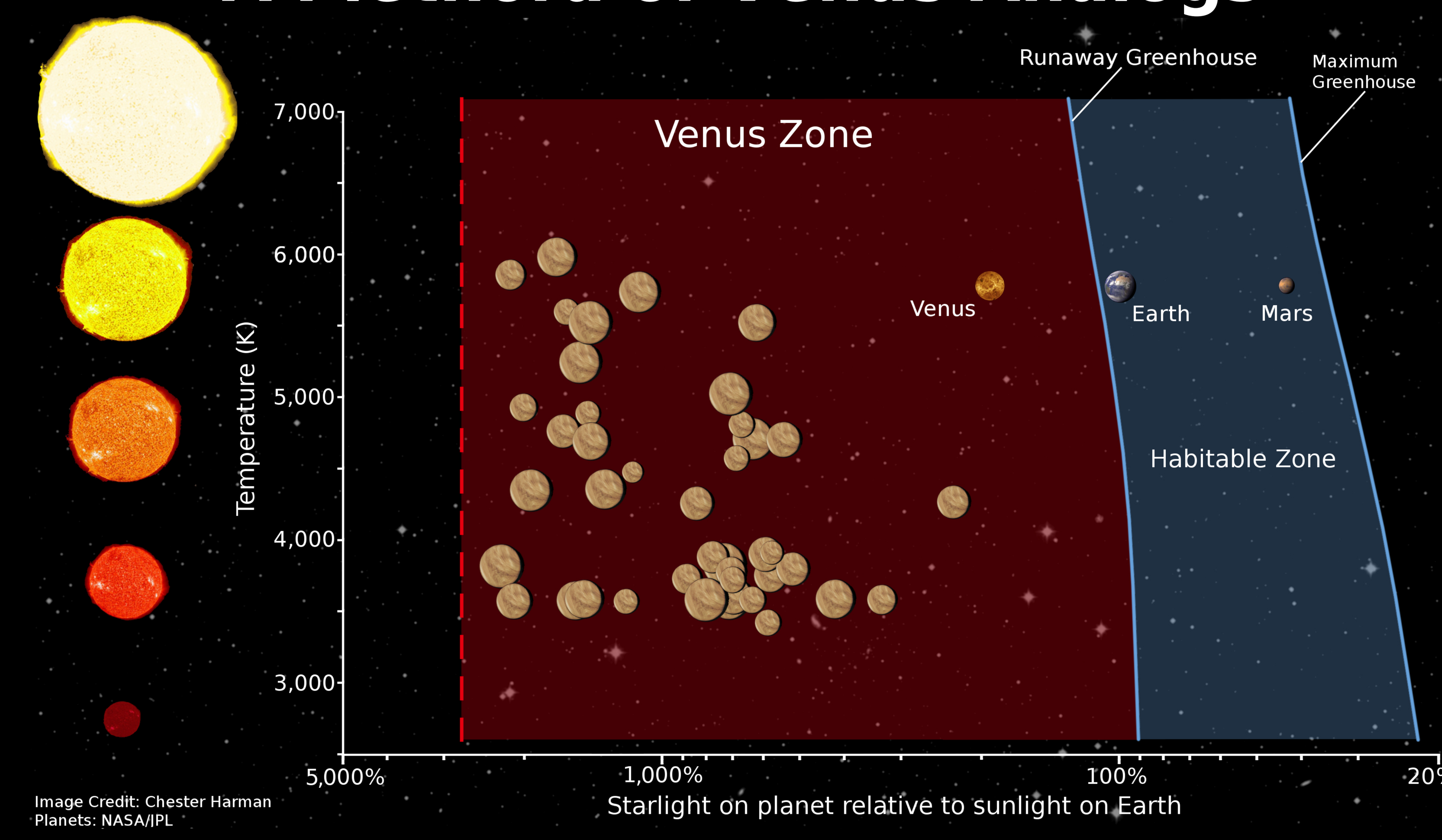
Evolution of Planetary Habitability

Venus provides a unique opportunity to explore the processes that created a completely uninhabitable environment and thus define the conditions that can rule out bio-related signatures. Indeed, Venus is the type-planet for a world that has transitioned from habitable conditions, through the inner edge of the Habitable Zone (HZ); thus it provides a natural laboratory to study the evolution of habitability. An incomplete understanding of the Venusian surface and atmospheric evolution will hinder the interpretation of exoplanet observations.

The below figure shows a timeline for Venus, Earth, and Mars based upon older interpretations of Venus mission data (Domagal-Goldman et al. 2016). This figure demonstrates the dramatic relative lack of knowledge that exists for the Venus timeline, particularly regarding the geological and atmospheric evolution, and the need to reassess the data and timeline with updated models.



A Plethora of Venus Analogs



Since the divergence of the Earth/Venusian atmospheric evolutions is a critical component for understanding Earth's habitability, the frequency of Venus analogs is also important to quantify. The Venus Zone (VZ), depicted in the figure above, has been proposed as a means to identify terrestrial planets where the atmosphere could potentially be pushed into a runaway greenhouse, producing surface conditions similar to those found on Venus (Kane et al. 2014).

The Transiting Exoplanet Survey Satellite (TESS) is providing further insight into the prevalence of Venus analogs, and will enable key opportunities for transmission spectroscopy follow-up observations. These studies will lead to a quantitative assessment of the primary contributors toward the emergence of runaway greenhouse atmospheres, allowing us to better understand the Earth/Venus divergence.

Interfacing to Venus Missions

Many significant questions remain on the current state of Venus that effectively inhibit our ability to model exoplanet environments. These include:

- *Did Venus have a habitable period (e.g. Way et al. 2016; Turbet et al. 2021)?*
- *Where did the water go? Was hydrogen loss and abiotic oxygen production rampant, or did surface hydration dominate?*
- *What has the history of tectonics, volatile cycling, and volcanic resurfacing been (Ivanov & Head 2011)? Does any surface subduction occur today (Smrekar et al. 2018; Byrne et al. 2021)?*
- *What is the detailed composition and atmospheric chemistry within the Venusian middle and deep atmosphere?*

Our exhaustive study of possible Venus evolution timelines, assessment of Venus analog occurrence rates, climate models of Venus analog candidates, and simulations of their spectra, will provide the most detailed analysis yet conducted regarding planetary habitability, both in our own and other planetary systems. The recent selection of DAVINCI+, VERITAS, and EnVision will also provide critical in-situ data for our habitability models and the inner edge of the VZ. Predictions on the evolution of Venusian habitability and development of exoVenus spectra will help to guide both Venus and exoplanet mission planning studies aiming to address these important topics.