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POSTER

A Limited Habitable Zone for Complex Life

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1. CO_2 and the Habitable Zone

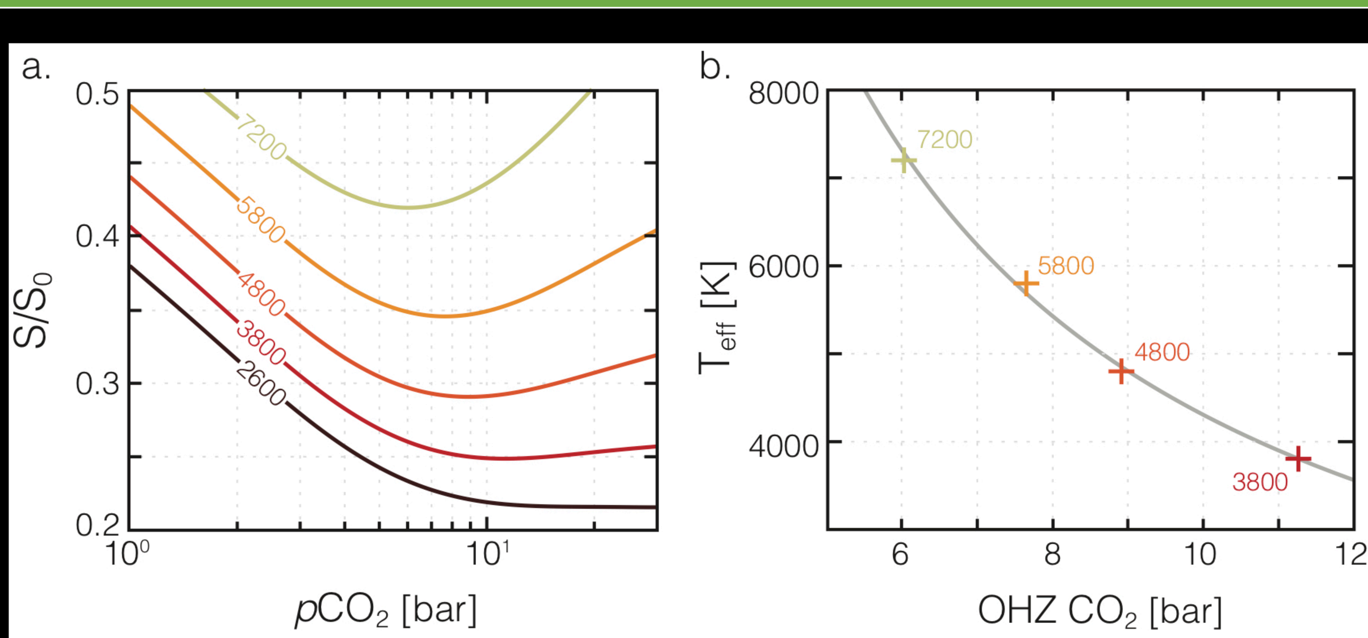

Figure 1: CO_2 Abundances at the Outer Habitable Zone (OHZ) boundary

One of the fundamental assumptions underlying the conventional HZ is that the carbonate-silicate cycle, in which atmospheric CO_2 levels are regulated by the effect of temperature on CO_2 consumption during rock weathering, will act to modulate atmospheric CO_2 concentrations (and thus surface temperatures) as a function of insolation (Walker et al. 1981). Near the inner edge of the habitable zone, clement surface temperatures can be maintained at low CO_2 concentrations similar to those of the modern Earth (tens to hundreds of ppm), but for the middle and outer regions of the HZ, atmospheric CO_2 concentrations need to be much higher in order to maintain temperatures conducive for surface liquid water—up to many bars approaching the outer edge. These OHZ CO_2 values represent the conventional "maximum greenhouse limit" above which Rayleigh scattering by CO_2 will lead to decreasing surface temperatures even as atmospheric CO_2 increases. **Figure 1** above shows the estimated atmospheric CO_2 at the outer edge of the Habitable Zone (OHZ). Shown in (a) are fits to a series of 1D radiative-convective climate models (Kopparapu et al. 2013) in which the effective stellar flux (S/S0) required to maintain a surface temperature of 273 K is computed as a function of atmospheric pCO_2 for a range of stellar hosts.

2. Physiological Limitations by high CO_2

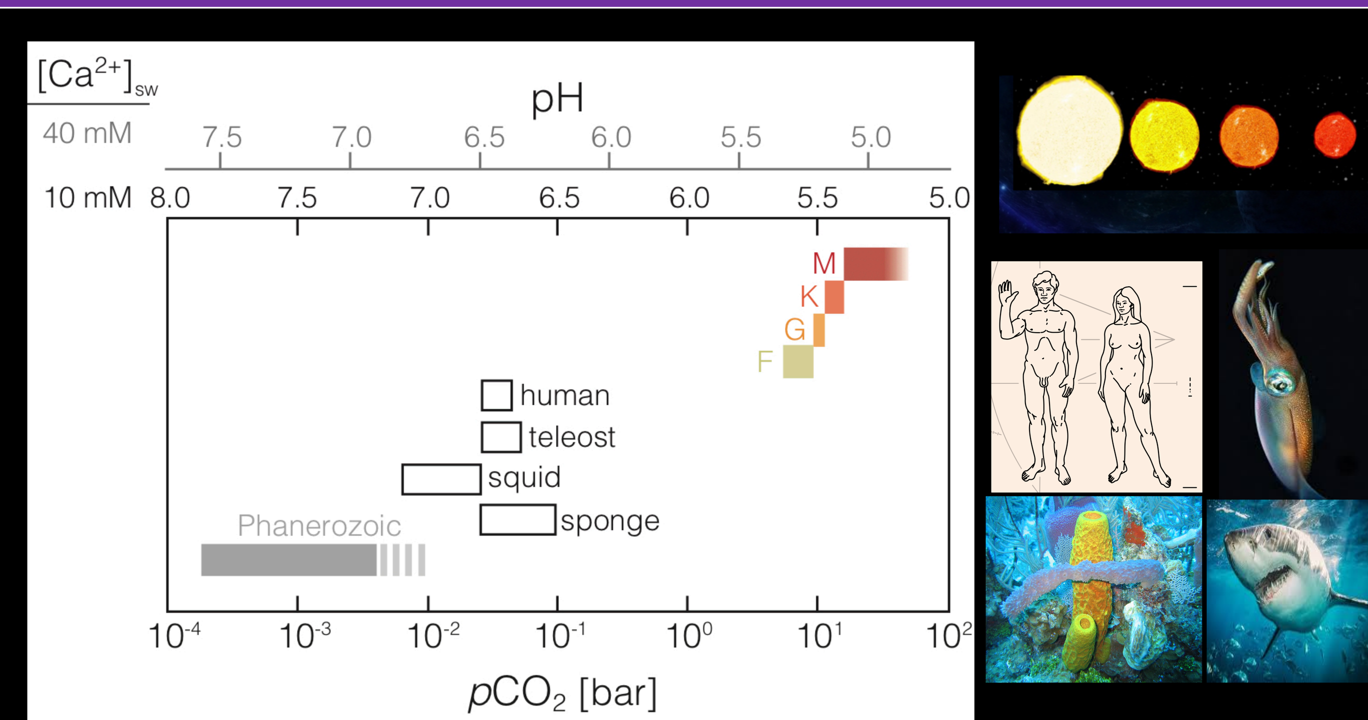

Figure 2: Physiological CO_2 limits and pH/CO_2 at the OHZ for FGKM stars

Elevated CO_2 levels can impose severe physiological stress on complex aerobic organisms (Pörtner et al. 2004; Wittmann & Pörtner 2013). Physiological responses to elevated CO_2 (hypercapnia) can be complex—often interacting across molecular, cellular, and organismal scales (Azzam et al. 2010)—but are most often regulated by respiratory acidosis and associated changes to ion buffering in internal fluids (Permentier et al. 2017). High atmospheric CO_2 also alters oceanic chemistry by lowering marine pH, with deleterious impacts on calcifying organisms and organisms that cannot effectively buffer internal pH (Wittmann & Pörtner 2013). In the figure above, open bars show upper long-term physiological CO_2 tolerances from a range of complex organisms on Earth. Grey bar shows the range of atmospheric pCO_2 levels during the Phanerozoic (540 million years ago to the present) according to geochemical proxies (solid)) and time-dependent biogeochemical models (dashed). Colored symbols show estimated values for pCO_2 at the outer edge of the habitable zone for F-, G-, K-, and M-type (red) stars. Upper scale shows marine pH assuming dissolved Ca2+ concentrations of 10 and 40 mmol kg^{-1}.

3. CO toxicity and Build-up for M star Hosts

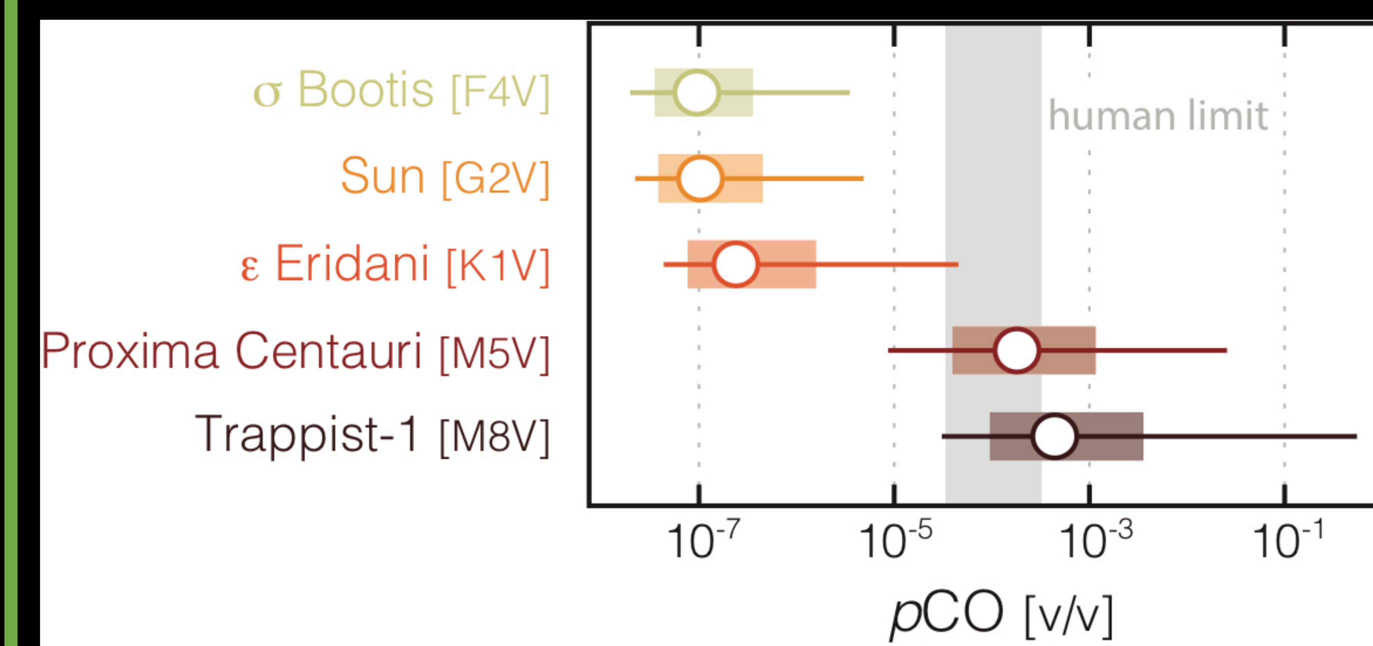

Figure 3: Harmful levels of CO predicted for Earth-like planets around M stars

An additional obstacle to complex life may be found in high-O_2 atmospheres on planets orbiting late-type stars, where certain photochemical conditions can lead to relatively high atmospheric CO levels (Schwieterman et al. 2019). CO is a highly toxic gas for humans and other vertebrates because their oxygen-carrying biomolecule hemoglobin has orders of magnitude higher bonding affinity for CO than for O_2 (Ryter & Otterbein 2004).

A planet with a high-O_2 atmosphere may accumulate harmful levels of CO as a result of direct or indirect production by the biosphere (e.g., fires) or geosphere (e.g., volcanism). For planets orbiting cool stars, a deficit of near-UV radiation results in substantially less OH production and greatly increased atmospheric lifetimes of CO, along with other important biogenic gases relevant for biosignature detection such as CH_4 (e.g., Segura et al., 2005). Importantly, the (primarily biological) flux of CO into our atmosphere is approximately twice the flux of CH_4.

4. Distribution of CO_2 in the Habitable Zone

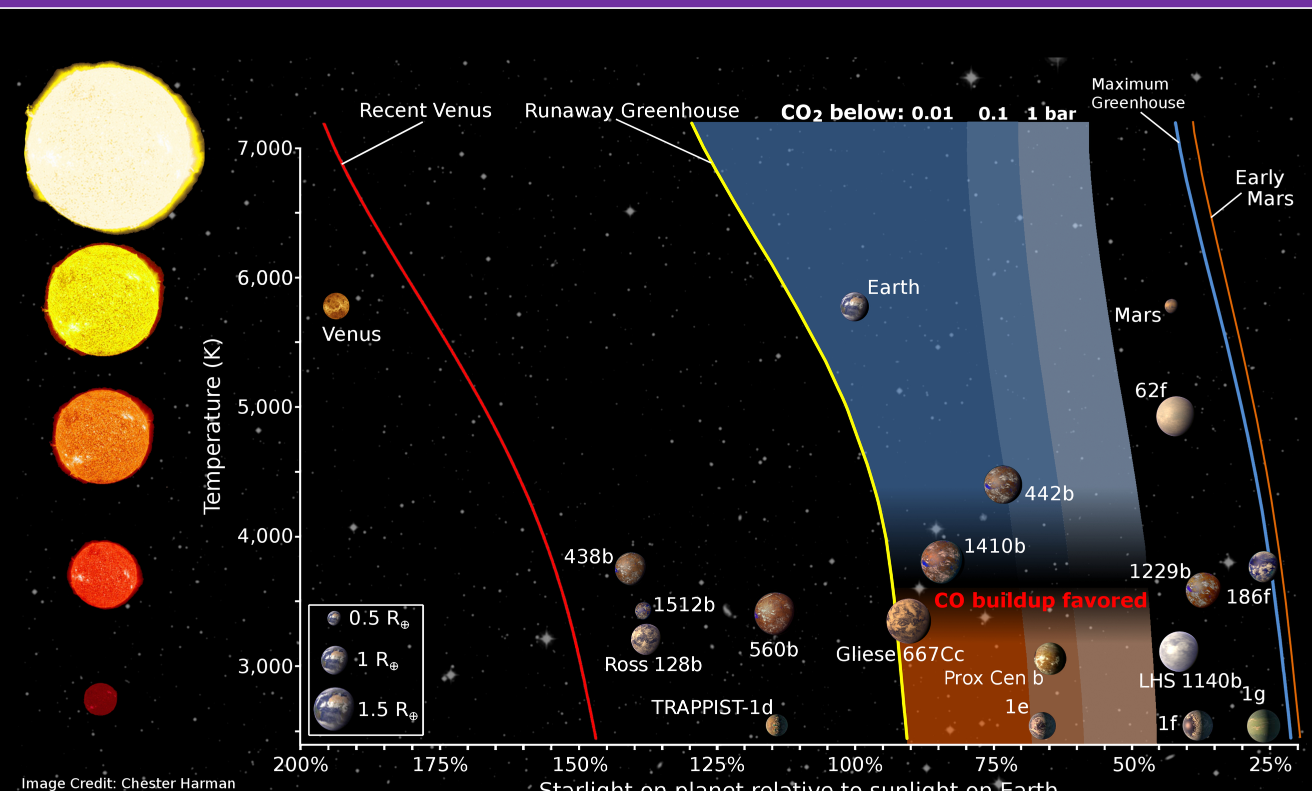

Figure 4: Minimum CO_2 levels to maintain non-freezing conditions as a function of insolation. High CO levels favored for low temp stars.

Considering the potential impacts of high atmospheric CO_2, we use a 1-D radiative-convective climate model to estimate the position of a Habitable Zone for Complex Life (HZCL). For each case, we assume a 1-bar bulk atmosphere composed of 78% N_2, 21% O_2, and 1% Ar, with additional CO_2 pressures (in bar) of 0.01, 0.1, and 1. We consider these CO_2 partial pressures to encompass conservative and optimistic ranges for long-term CO_2 limitation of complex aerobic life at 0.2 bar O_2—barring any currently unknown physiological mechanism for mitigating long-term hypercapnia at extremely high CO_2. We estimate that physiological CO2 thresholds of 0.01, 0.1, and 1 bar correspond to HZCLs that are only 21%, 32%, and 50% as wide as the conventional HZ for a Sun-like star, with slightly smaller HZs for stars with lower effective temperatures.

5. A Habitable Zone for Complex Life

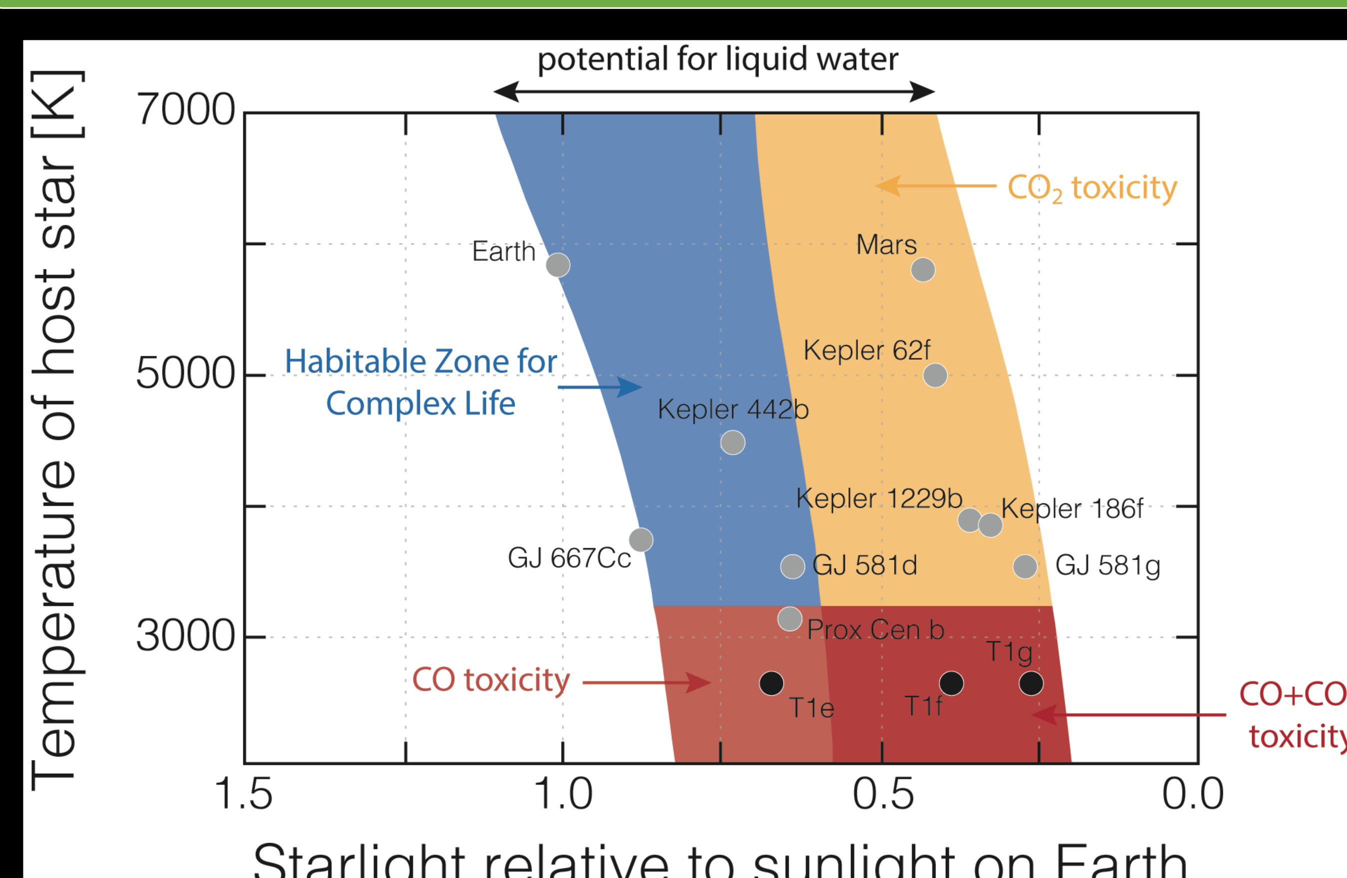

Figure 5: The "Habitable Zone for Complex Life" (blue, pCO2 < 0.1 bar) is highly restricted relative to the zone defined by the potential for liquid water, due to toxic buildup of CO_2 (yellow), CO (red), or both (orange). This "safe zone" excludes many potentially water-bearing exoplanets, including Proxima Centauri b and TRAPPIST-1e, f, and g (black dots).

Figure 5 illustrates the combined impact of physiological limitations of CO_2 and CO with our climate and photochemical results. Our photochemical model results suggest that high CO concentrations may limit some forms of complex life for host stars with T_{eff} < 3,200 K. These results further suggest that the regions of habitability available for complex life (as it know it on Earth) are significantly smaller than conventional circumstellar habitable zones.

6. Discussion and Conclusions

- Our results have a number of important implications for the search for exoplanet biosignatures and complex life beyond our solar system. For example, our predictions of a more limited zone for complex life place constraints on the planetary environments suitable for the evolution of intelligence, if it requires free O_2 and limited concentrations of CO_2, CO, and other potentially toxic trace gases. One implication is that we may not expect to find remotely detectable signs of intelligent life ('technosignatures') on planets orbiting late M dwarfs or on potentially habitable planets near the outer edge of their HZs.
- Limitations on complex life by CO_2 and CO may partially address why we find ourselves near the inner edge of the habitable zone of a G-dwarf star rather than near the center or toward the outer edge of the habitable zone around one of the much more numerous M-dwarf stars (Waltham 2017; Haqq-Misra et al. 2018), as this condition is most favorable from the perspectives of both CO_2 drawdown and limited toxic gas abundance.
- Our results highlight the importance of a planet's relative HZ location and atmospheric photochemistry in constraining the planetary potential for complex life. We suggest that the expected physiological impacts of high CO_2, CO, and other gases possibly toxic for complex life should be considered in attempts to search for biological complexity beyond our solar system.

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