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CO_2, CO, and CH_4 abundance in the anoxic atmosphere of Earth-like exoplanets and its implications for the search for habitable planets

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The traditional concept of planetary habitability relies mainly on the presence of liquid water on a planet. However, several environmental factors, such as the climatic state and availability of bioessential elements, also affect it. From this perspective, carbon is of particular interest, not only because it is an essential element for Earth's life, but also because the abundance of major carbon species (CO_2, CO, and CH_4) in the atmosphere plays a key role in the planetary climate and biogeochemistry. Thus, a quantitative understanding of the factors that control the relative abundance of these carbon species in the planetary atmosphere has far-reaching implications for the search for habitable planets beyond our solar system. Here, we employ a theoretical model of atmospheric chemistry to explore the relative abundance of CO_2, CO, and CH_4 in the anoxic atmosphere of a hypothesized Earth-like planet around G, F, and M type stars, with particular attention to the conditions for a CO-rich atmosphere. Our results demonstrate that elevated CO_2 levels tend to lead to the so-called CO runaway phenomenon by promoting CO_2 photolysis relative to H_2O photolysis. High volcanic outgassing fluxes of H_2 also promote the CO runaway by removing OH radical from the atmosphere. Once the CO runaway is triggered, atmospheric CO levels dramatically increase (typically ~0.1-0.3 bar for the Archean Earth). When we plot steady states in the phase diagram of atmospheric CH_4/CO_2 vs. CO/CO_2, there is a clear gap at which atmospheric CO level is highly dependent on CH_4. Our sensitivity experiments with respect to different spectrum types of central stars also suggest that this gap structure would be a general feature of the anoxic Earth-like planets, providing ramifications for the search for habitable planets that may promote the origin of life.