

Effect of orbital distance and volcanic gas compositions on atmospheric CO partial pressures of Earth-like lifeless planets

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Atmospheric composition is an essential factor in determining the habitability of planetary surface environments. The compositions of secondary atmospheres of lifeless Earth-like planets would be determined by volcanic gas composition, atmospheric chemical reactions, and the carbonate-silicate geochemical cycle. Carbon monoxide (CO), primarily produced by CO₂ photolysis, plays a crucial role in prebiotic chemistry due to its ability to facilitate organic synthesis and support primitive organisms. Previous modeling studies predict that the atmospheric CO partial pressures (p_{CO}) could be extremely high (>0.01 bar) in CO₂-rich atmospheres (e.g., Kasting et al., 1983; Watanabe and Ozaki, 2024). Specifically, atmospheric compositions under various atmospheric CO₂ partial pressures (p_{CO_2}), volcanic outgassing fluxes, surface temperatures, and the spectral types of central stars have been assessed systematically (Watanabe and Ozaki, 2024). They found that atmospheric p_{CO} tends to be higher at higher atmospheric p_{CO_2} , higher volcanic outgassing fluxes, lower surface temperatures, and cooler host stars. However, in reality, atmospheric p_{CO_2} and surface temperature are regulated by the geochemical carbon cycle, which is influenced by volcanic degassing rates and orbital distance (or incident stellar flux). The extent to which CO-rich atmospheres can form under plausible volcanic conditions on early Earth and Earth-like exoplanets remains uncertain.

Here, we employed a thermodynamic model of volcanic gas composition (Wogan & Catling, 2020) to calculate magma degassing. We also employed a zero-dimensional energy balance model coupled with a global carbon cycle model (Krissansen-Totton et al., 2018) and estimated the atmospheric p_{CO_2} and surface temperature under a given CO₂ outgassing rate and orbital distance from a central star. Using these variables as input, we then conducted atmospheric photochemical modeling using a one-dimensional photochemical model *Atmos* (Arney et al., 2016). Using this model, we investigated the impact of the changes in orbital distance from a central star, net outgassing rate, and redox state of volcanic gases. Our results demonstrate that the atmospheric p_{CO} increases with orbital distance from a central star. In contrast, formaldehyde production rates decrease with increasing orbital distance from a central star. Compared to early Earth, early Mars may have had an advantage in organic matter production due to its reducing volcanic gases, but its larger orbital distance would have been a disadvantage. In future searches for life on exoplanets, it would be preferable to target planets that are not too distant from their host stars.

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