NOTE: This version corrects minor typos and updates the Methods section of *RNAAS* version

IMPLICATIONS OF REVISED CO₂-CH₄ AND CO₂-H₂ ABSORPTION FOR OUTER EDGE HABITABLE ZONE PLANETS

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INTRODUCTION

The habitable zone (HZ) is the region around a star where standing bodies of liquid water could be stable on a planetary surface (Ramirez, 2018). Potentially habitable planets near the outer edge of the classical HZ are assumed to consist of multi-bar CO₂ atmospheres (e.g., Kasting et al., 1993). However, recent extensions of the HZ concept show that secondary greenhouse gases, like CH₄ and H₂, can complement the greenhouse warming by CO₂, further increasing the size of the HZ (Ramirez and Kaltenegger, 2017; 2018). These later studies had incorporated new data from CO₂-CH₄ and CO₂-H₂ collision-induced absorption (CIA) pairs, which Wordsworth et al. (2017) showed to have a significantly stronger greenhouse effect than those of N₂-CH₄ and N₂-H₂, previously used as proxies for CO₂-CH₄ and CO₂-H₂ CIA (Ramirez et al. 2014).

However, this CO₂-CH₄ and CO₂-H₂ CIA had not been experimentally-determined but was instead computed via ab initio calculations (Wordsworth et al., 2017). Indeed, recent laboratory measurements verified that such ab initio calculations overestimate CO₂-CH₄ and CO₂-H₂ CIA (Turbet et al., 2019). Nevertheless, this revised absorption was still found to be stronger than that from N₂-CH₄ and N₂-H₂ CIA pairs.

Thus, the true outer edge of the CO₂-CH₄ and CO₂-H₂ HZ may not be quite as far as that predicted in previous work (Ramirez and Kaltenegger, 2017; 2018). However, the Turbet et al. CIA have large error bars and more precise measurements are needed to refine them. Nevertheless, the CO₂ ab initio CIA pairs and the N₂ CIA proxies can bracket the possibilities. In this research note, I will compare the HZ outer edge limits computed using the older (N₂-CH₄ and N₂-H₂) CIA against those previously calculated with the newer ab initio (CO₂-CH₄ and CO₂-H₂) values (Ramirez and Kaltenegger, 2017; 2018) and discuss implications.

METHODS

I use my single-column radiative-convective climate model (e.g. Ramirez and Kaltenegger, 2017; 2018) to calculate the effect of adding different amounts of CH₄ and H₂ to the classical CO₂ HZ outer edge comparing atmospheres with N₂ or CO₂ as the broadening agent (Figure 1). All atmospheres are assumed to be fully-saturated. Stratospheric temperature is assumed to be a constant 154 K for the H₂ calculations (e.g. Ramirez and Kaltenegger, 2017) whereas it is self-consistently computed in the CH₄ calculations (Ramirez and Kaltenegger, 2018).

RESULTS

Adding 10% H₂ decreases the effective stellar flux (S_{EFF}), which is the normalized flux received by the Earth (1360 W/m^2), from ~ 0.36 to 0.25 and 0.28 for CO₂-H₂ and N₂-H₂ CIA, respectively, for a Sun-like (5800 K) star (Figure 1). From the inverse-square law, and for a normalized solar luminosity value of 1 for the Sun, the outer edge distances increase from ($\sqrt{1/0.36}$) 1.67 AU to ~ 2 and 1.89 AU, respectively.

In contrast, with the CO₂-CH₄ CIA, CH₄ has a warming effect for stars hotter than ~ 4500 K and a cooling effect for colder stars (Ramirez and Kaltenegger, 2018). This threshold increases from 4500 K to ~ 5700 K with the older (N₂-CH₄) CIA. Repeating the same calculation for the Sun, the outer edge distance increases from 1.67 AU to $\sim (\sqrt{1/0.325})$ 1.75 AU and ($\sqrt{1/0.35}$) 1.69 AU for CO₂-CH₄ and N₂-CH₄ CIA, respectively.

Figure 1: The effect of adding (a) 1% or 10 ppm methane (blue) and (b) 5% or 10 % hydrogen (red) to outer edge habitable zone planets with both CO₂ (solid red or blue lines) and N₂ (dashed red or blue lines; old) CIA. The traditional outer HZ limit, the CO₂ maximum greenhouse limit (solid black lines) is shown. Solid lines are calculations reproduced from Ramirez and Kaltenegger (2017;2018).

DISCUSSION

My results here confirm previous studies showing that CIA broadened by CO₂ is stronger than that by N₂ (e.g. Wordsworth et al., 2017; Turbet et al., 2019). Unsurprisingly, more accurate CO₂-H₂ CIA should reveal results in between those of the ab initio and N₂-H₂ calculations. In any case, the effects of CO₂-H₂ CIA on the HZ outer edge would still be significant, especially for H₂ concentrations exceeding those considered here. These results also suggest that a CO₂-H₂ greenhouse on early Mars would remain potent as well (e.g. Ramirez, 2017).

The situation with CH₄ CIA is even more interesting. Although, both CIA sets show that CH₄ becomes a cooling gas below a threshold stellar effective temperature, this cooling is even more pronounced with the weaker N₂-CH₄ CIA (Figure 1). Likewise, the outer edge extends farther out with the stronger CO₂-CH₄ CIA.

Even more importantly, revised CO₂-CH₄ cross-sections with absorption strength in between the two should reveal that CH₄ cools HZ planets over a larger stellar effective temperature than the ~2600 - 4500 K originally computed with the ab initio CO₂-CH₄ values (Ramirez and Kaltenegger, 2018). A mid-point calculation (0.5 x (4500 + 5700)) suggests that the stellar effective temperature below which CH₄ becomes a cooling gas on HZ planets may be around ~5100 K, well into the G-star range (Figure 1).

Finally, this surface cooling occurs independently of haze formation and whether or not such hazes cool M-star planets (e.g. Arney et al., 2017). It also occurs even at low CH₄ concentrations (e.g. ppm level) (Figure 1). Such results also suggest that methanogenesis (a process on Earth by which methanogenic bacteria react CO₂ with free H₂, forming CH₄) may not be an effective process for life on HZ planets orbiting many stars. This is because methanogenesis would cool such planets, possibly leading to runaway glaciation and atmospheric collapse, unless their host stars are hot enough (Ramirez and Kaltenegger, 2018).

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