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On the detection of carbon monoxide as an anti-biosignature in exoplanetary atmospheres

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ABSTRACT

Recent works suggest that oxygen can be maintained on lifeless exoplanets in the habitable zones of M dwarfs as the results of photochemical reactions. However, the same photochemical models also predict high concentrations of carbon monoxide (CO) in the corresponding atmospheres. Here we use a line-by-line radiative transfer model to investigate the observation requirements of O_2 and CO in such atmospheres. The results show that photochemically produced CO can be readily detected at 1.58, 2.34, and 4.67 μm. We suggest that future missions aiming at characterization of exoplanetary atmospheres consider detections of CO as an anti-biosignature.

1. Introduction

Earth-sized rocky planets are common in the habitable zones of M dwarfs (Dressing and Charbonneau, 2013, 2015; Gaidos, 2013; Kopparapu, 2013; Tuomi et al., 2014). Although most observation feasibility considerations favor M dwarfs as the most promising targets in the search for habitable exoplanets and life in the near future, atmospheric composition of habitable exoplanets are strongly affected by the unique UV spectra of M dwarfs (France et al., 2012, 2013; Hu et al., 2012; Tian et al., 2014; Domagal-Goldman et al., 2014; Luger and Barnes, 2015; Gao et al., 2015; Harman et al., 2015). In particular, atmospheres with 5% CO_2 on abiotic Earth-mass planets with Earth-like climate around M dwarfs could contain 10^{-3} level of O_2 as a consequence of slow photolysis of H_2O and H_2O_2 (Tian et al., 2014; Harman et al., 2015). If the atmospheres are dominated by CO_2 and the exoplanets are desiccated because of early stellar luminosity evolution (Ramirez and Kaltenegger, 2014; Tian and Ida, 2015; Luger and Barnes, 2015), atmospheric oxygen could even reach 1–10% (Gao et al., 2015). Interestingly the CO contents in these hypothetical atmospheres are always on the same order of magnitude as that of O_2: 10^{-3} in Tian et al. (2014) and 1–10% in Gao et al. (2015).

CO can act as an energy source for some microbes on the Earth (Walker, 1977; Des Marais, 1998; House et al., 2003; Battistuzzi et al., 2004). It is estimated that CO deposition velocity on an abiotic Earth would have been on the order of 10^{-8}–10^{-9} cm/s, 4 or 5 orders of magnitude lower than that after the development of acetogens (Kharecha et al., 2005) – it is more difficult for CO to accumulate in the atmosphere of an inhabited planet. Thus detection of high level of atmospheric CO may be regarded as an anti-biosignature. A somewhat weaker statement has also been proposed: the lack of some species which should be present due to natural processes, such as CO through photochemistry on M dwarf exoplanets, could also be a biosignature (Eric Gaidos, private communication). Thus the detection of CO itself could be interesting for atmosphere characterization of habitable zone rocky exoplanets around M dwarfs.

Whether the high atmospheric oxygen and CO contents are observable by future exoplanetary atmosphere characterization missions/facilities is one question we aim to address in this work. In Section 2, we introduce the radiation transfer model (LT model) used in this work. Results are shown in Section 3. In Section 4, we estimate the observation time needed to resolve O_2 and CO predicted to exist in the atmospheres of habitable zone rocky planets of M dwarfs. Conclusion are summarized in Section 5.

2. Model description

The LT model (Li and Tian, 2012) is a line-by-line model developed to calculate the transmission, reflection, and emission spectra of exoplanets. It uses the line intensities and half-widths

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(both self-broadening and air-broadening) from the HITRAN2012 database (Rothman et al., 2013). Voigt line shape profiles are used for all gases with cut-off distances set to 50 times Voigt half-widths from line centers. An incidence and reflection angles of 60° in a plane-parallel atmosphere are used to approximate the geometry integration of exoplanets, consistent with the approaches in previous works (Des Marais et al., 2002; Kaltenegger et al., 2007).

The default resolution of the LT model is 0.01 cm^{-1} between 0.5 and 10 μm, corresponding to $R = \lambda/\Delta\lambda = 2 \times 10^6$ and 10^5 at 0.5 and 10 μm respectively, adequate to resolve all major absorption lines in the HITRAN2012 database. In comparison, the High Resolution Echelle Spectrometer (HIRES) of Keck I Telescope has R = 25,000–85,000 at 0.3–1 μm (Vogt et al., 1994; Oke et al., 1995), with the range based on the choice of slit plate in observations. The Low Resolution Imaging Spectrometer (LRIS) of Keck I Telescope has R = 300–5000 at 0.3–1 μm. The Near-Infrared Spectrograph (NIRSPEC) of Keck II Telescope has R = 25,000 and 2500 at 0.95–5.5 μm (McLean et al., 1998). The moderate and low resolutions of James Webb Space Telescope (JWST) are R = 1000 and 100 between 0.6 and 5.0 μm (Wright et al., 2004; Bagnasco et al., 2007). All results shown here are R = 100 spectra smoothed from high resolution LT spectra.

The main absorption bands of O_2 are 0.69 μm (B band), 0.76 μm (A band), and 1.27 μm. Even with a low concentration (~0.1 ppmv) in the Earth's atmosphere, CO can be recognized at 4.67 μm and 2.34 μm (Fig. 3.1 in Goody and Yung, 1989). CO 1.58 μm feature is invisible at the surface of the Earth with 50 cm^{-1} spectral resolution (corresponds to roughly R = 128) (Liou, 2002). The non-detection of CO 1.58 μm feature is partially due to the weakness of this absorption band and partially due to the overlapping CO_2 absorption. For exoplanets the concentration of CO could be much greater than that in the Earth's atmosphere. Thus CO 1.58 μm absorption band is included in this study. For exoplanets at Earth-equivalent distances, the emission from the planets far exceeds the reflected stellar radiation near 5 μm. To take this effect into consideration, the calculated planetary emission spectrum at the top of the atmosphere (TOA) is divided by the incident stellar spectrum and the ratio is included in the reflectivity calculations. The incident stellar spectrum is a blackbody spectrum at 3500 K with the total energy flux scaled to 1360 W/m^2, the solar constant of modern Earth (Kopp and Lean, 2011). Note that this incident flux is only used to calculate the reflection spectrum.

For simplicity purpose, a wavelength dependent planetary surface albedo, which includes the combined effects of clouds, aerosols, and surface type, is used in this work. Based on observations of the Earth (Jin et al., 2014; Turnbull et al., 2006), the surface albedo is set to 0.28 for 0.6–1.1 μm, 0.26 for 1.1–1.4 μm, 0.21 for 1.4–1.8 μm, and 0.17 for 1.8–2.4 μm, respectively. The NIR spectrum of the Earth calculated by the LT model with these surface albedo and modern Earth atmospheric composition profiles resembles the observed globally averaged reflectance spectrum (Jin et al., 2014). Observations for 4.5–5 μm is scarce. Considering the surface types and cloud scattering properties, a surface albedo of 0.15 is used. Our results are insensitive to this assumption. For planets with Earth-like climate, planetary emission dominates in this wavelength range. For desiccated exoplanets, 1.58 and 2.34 μm are the best wavelengths for CO detection. The lack of water vapor makes CO features more obvious in 2.34 μm. Thus setting 0.15 albedo for 4.5–5 μm should not significantly change the detectability of CO.

For exoplanets with Earth-like climate, the mixing ratios of CO_2, CO, and O_2 (altitude-independent) are set to 5%, 0.5%, and 0.2% respectively based on Tian et al. (2014). The temperature and H_2O profiles are also from Tian et al. (2014). For desiccated

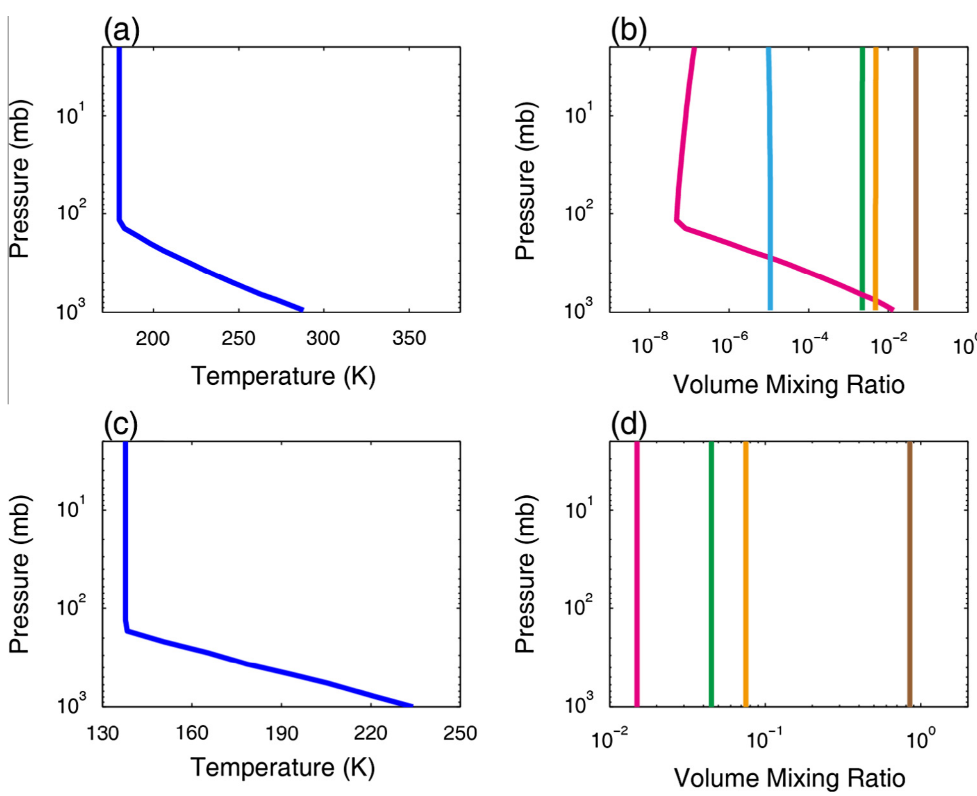

Fig. 1. Temperature and composition profiles in Tian et al. (2014) (panel a, panel b) and in Gao et al. (2015) (panel c, panel d). The green, orange, pink, brown, and light blue curves in panel b and d represent O_2, CO, H_2O, CO_2 and CH_4 respectively. The H_2O mixing ratio in panel d is multiplied by 10^5. The H_2O contents are far blow saturation and thus its mixing ratio is constant in the lower atmosphere. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)