

New insights into martian atmospheric chemistry



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ABSTRACT

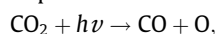
HO_x radicals are produced in the martian atmosphere by the photolysis of water vapor and subsequently participate in catalytic cycles that recycle carbon dioxide (CO₂) from its photolysis product carbon monoxide (CO), providing a qualitative explanation for the stability of its atmosphere. Balancing CO₂ production and loss based on our current understanding of martian gas-phase chemistry has, however, proven to be difficult. The photolysis of O₃ produces O(¹D), while oxidation of CO produces HOCO radicals, a new member of the HO_x family. The O(¹D) quantum yield has recently been updated, which quantifies non-zero quantum yields in the Huggins bands. In Earth's atmosphere HOCO is considered to be unimportant since it is quickly removed by abundant oxygen molecules. The smaller amount of O₂ in the Mars' atmosphere causes HOCO's lifetime to be longer in Mars' atmosphere than Earth's (3 × 10⁻⁵ s to 1.2 days from Mars's surface to 240 km, respectively). Limited kinetic data on reactions involving HOCO prevented consideration of its reactions directly in atmospheric models. Therefore, the impact of HOCO reactions on martian chemistry is currently unknown. Here, we incorporate new literature rate constants for HOCO chemistry and an updated representation of the O(¹D) quantum yield in the Caltech/JPL 1-D photochemical model for Mars' atmosphere. Our simulations exemplify perturbations to NO_y, HO_x, and CO_x species, ranging from 5% to 50%. The modified O(¹D) quantum yield and new HOCO chemistry cause a 10% decrease and a 50% increase in OH and H₂O₂ total column abundances, respectively. At low altitudes, HOCO production contributes 5% towards CO₂ production. Given recent experimentally-obtained branching ratios for the oxidation of CO, HOCO may contribute up to 70% toward the production of NO_y, where HO_x and NO_y species are enhanced up to a factor 3, which has implications for rethinking the fundamental understanding of NO_y, HO_x, and CO/CO₂ cycling on Mars. Two new reaction mechanisms for converting CO to CO₂ using HOCO reactions are proposed, which reveal that H₂O₂ is more intimately coupled to CO_x chemistry. Our simulations are in good agreement with satellite/spacecraft measurements of CO and H₂O₂ on Mars.

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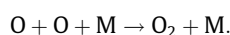
1. Introduction

Mars continues to be a test-bed for space exploration for finding extraterrestrial life. At present, finding life on Mars may not be limited by essential life nutrients, such as water and nitrogen

(Boxe et al., 2012a,b). It's atmosphere is comprised primarily of carbon dioxide (Owen et al., 1977), approximately ~95%, which is readily photolyzed by solar ultraviolet radiation below 205 nm to produce carbon monoxide (CO) and atomic oxygen (O):



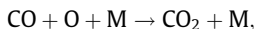
where atomic oxygen forms O₂ via the following reaction:



Once CO₂ is converted into CO and O, it is difficult to restore it. This is primarily due to the fact that the following reaction,

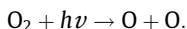
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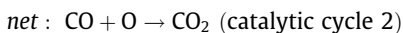
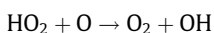
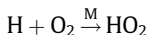
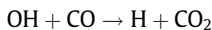
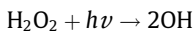
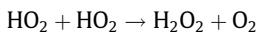
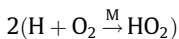
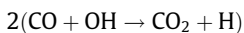
is spin-forbidden, and its three-body reaction rate coefficient is many orders of magnitude slower than the formation channel for O_2 shown above. Therefore, the net result of the of CO_2 photolysis is $2\text{CO}_2 \rightarrow 2\text{CO} + \text{O}_2$.

Within the context of a pure CO_2 atmosphere, the amounts of CO and O_2 would undoubtedly be very large, even when considering the photodissociation of O_2 :

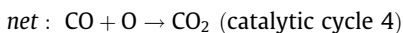
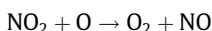
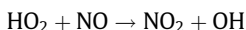
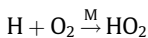
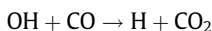
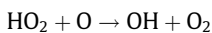
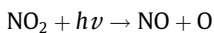
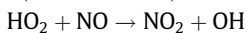
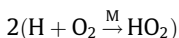
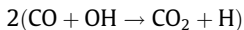


Specifically, this scenario yields CO and O_2 mixing ratios of 7.7×10^{-2} and 3.8×10^{-2} , respectively, and a CO: O_2 ratio of 2:1, which is in contradiction to the observed mixing ratios (7.0×10^{-4} for CO and 1.3×10^{-3} for O_2) and ratio of 0.5 (Yung and Demore, 1999). This suggests that another process stabilizes the observed CO_2 concentration of the martian atmosphere.

The stability of CO_2 in the martian atmosphere appeared to be a contradiction to known chemical kinetics for a pure CO_2 atmosphere, where for Mars, there was substantially smaller amounts of CO and O_2 – previously termed the CO_2 stability problem. It is well known that HO_x (H, OH, HO_2) chemistry plays an important role in stabilizing the CO_2 dominated atmosphere of Mars (McElroy and Donahue, 1972; Parkinson and Hunten, 1972). According to chemical mechanisms proposed by McElroy and Donahue (1972) (catalytic cycle 1) and Parkinson and Hunten (1972) (catalytic cycle 2), CO is then effectively converted back to CO_2 via reactions with HO_x .



McElroy and Donahue (1972) and Parkinson and Hunten (1972) recognized that the small amount of water vapor in Mars's atmosphere could play a fundamental role in atmospheric photochemical processes. Since these seminal investigations, the only significant addition involved the reaction of HO_2 with NO to yield NO_2 and OH, which introduced 2 new chemical schemes for the oxidation of CO to CO_2 (Nair et al., 1994; Yung and Demore, 1999).



Since Nair et al. (1994), there has not been any significant update on addressing the CO– CO_2 cycling on Mars. The $\text{O}(^1\text{D})$ quantum yield has recently been updated, which quantifies nonzero quantum yields in the Huggins bands (Matsumi et al., 2002). In addition, it is also known that the OH + CO reaction produces HOCO, a radical species, whose impact has never been considered in the martian atmosphere, given the once limited kinetic data on reactions involving HOCO (Petty et al., 1993; Olkhov et al., 2001; Mielke et al., 2003; Yu et al., 2005). We, therefore, utilize the Caltech/JPL 1-D photochemical model for Mars to look at the impact on the chemical state of its atmosphere via the inclusion of updated $\text{O}(^1\text{D})$ quantum yields (Matsumi et al., 2002) and HOCO chemistry (Fulle et al., 1996; Sears et al., 1992) (Table 1). Firstly, the photochemical model setup is briefly described; thereafter, the impact on NO_y , HO_x , and CO_x chemistry are discussed in Section 3.

2. Photochemical model setup

We utilize the Caltech/JPL one-dimensional (1-D) photochemical kinetics model for a latitude of 30° versus season, which is similar to that used by Yung et al. (1988) and Nair et al. (1994) to study the, overall, photochemical state of the martian atmosphere. A detailed description of the 1-D photochemical model can be found in Nair et al. (1994); we, therefore, only provide a short description of the model. Specifically, it incorporates Mars atmospheric O_x , CO_x , HO_x , and NO_y chemistry in the presence of vertical diffusive transport and allows for time-dependent calculations. This model is an update of the Nair et al. (1994) model. It solves the 1-D continuity equation,

$$\frac{\partial n_i}{\partial t} + \frac{\partial \Phi_i}{\partial z} = P_i - L_i,$$

(n_i , Φ_i , P_i , and L_i are the concentration, vertical diffusive flux, and chemical production and loss terms, respectively, for species i (Allen et al., 1981) for 29 species (O, $\text{O}(^1\text{D})$, O_2 , O_3 , N, $\text{N}(^2\text{D})$, N_2 , N_2O , NO, NO_2 , NO_3 , N_2O_5 , HNO_2 , HNO_3 , HO_2NO_2 , H, H_2 , H_2O , OH, HO_2 , H_2O_2 , CO, CO_2 , O^+ , O_2^+ , CO_2^+ , and CO_2H^+) in 177 reactions from the surface to the exosphere at 240 km (with 2 km resolution) in 121 levels. In the diurnally-averaged 1-D photochemical model, the steady-state solution is solved after allowing $\frac{\partial n_i}{\partial t} \rightarrow 0$. The vertical flux is given by

$$\Phi_i = -D \left(\frac{dn_i}{dz} + \frac{n_i}{H_i} + \frac{n_i(1 + \alpha)}{T} \frac{dT}{dz} \right) - K \left(\frac{dn_i}{dz} + \frac{n_i}{H_i} + \frac{n_i}{T} \frac{dT}{dz} \right),$$

where D_i is the molecular diffusion coefficient of species i through the background atmosphere, H_i is the scale height of species i , T is the temperature, α is the thermal diffusion factor (which we take to be zero), K is the eddy diffusion coefficient, and H is the scale height of the background atmosphere.

Table 1

New reactions included in the JPL/Caltech 1-D Photochemical Mars Model. Rate coefficients are given in $\text{cm}^3 \text{molecule}^{-1} \text{s}^{-1}$ for bimolecular and $\text{cm}^6 \text{molecule}^{-2} \text{s}^{-1}$ for termolecular reactions.

Reaction	Rate coefficient	Reference
R_1 OH + CO + M \rightarrow M + HCO ₂	$k_0 = 5.90\text{E}-33$ $(T/300)^{-1.4}$	Sander et al. (2006)
R_2 HCO ₂ + O ₂ \rightarrow HNO ₂ + CO ₂	2.00×10^{-12}	Sander et al. (2006)
R_3 HCO ₂ + HO ₂ \rightarrow H ₂ O ₂ + CO ₂	5.80×10^{-11}	Yu et al. (2008)
R_4 HCO ₂ + HO ₂ \rightarrow 2O ₂ + CO ₂	6.50×10^{-12}	Yu et al. (2008)
R_5 HCO ₂ + H \rightarrow H ₂ + CO ₂	1.00×10^{-10}	Yu and Francisco (2008)
R_6 HCO ₂ + H \rightarrow H ₂ O + CO	4.00×10^{-12}	Yu and Francisco (2008)
R_7 HCO ₂ + OH \rightarrow H ₂ O + CO ₂	1.00×10^{-11}	Yu et al. (2005)
R_8 HCO ₂ + NO \rightarrow HNO ₂ + CO	2.00×10^{-12}	Olkhov et al. (2001)

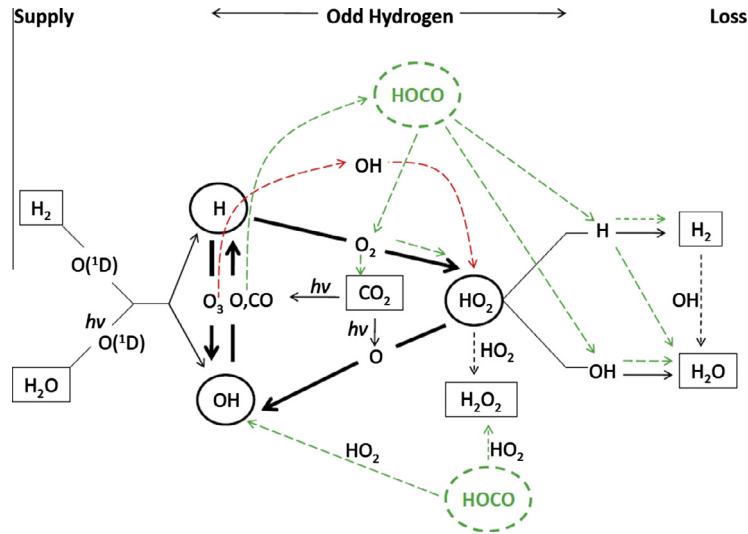


Fig. 1. Schematic diagram showing the principal pathways for reactions involving hydrogen species. The red and green arrows illustrate new reactions included in the Caltech/JPL 1-D photochemical sourced from O₃ photolysis and the OH + CO reaction, which affect odd hydrogen chemistry. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Results and discussion

The HOCO chemistry completely represents all reactions sourced from the termolecular reaction pathway that produces HOCO (Petty et al., 1993; Olkhov et al., 2001; Clements et al., 2002; Yu et al., 2005, 2008; Sander et al., 2006; Lu et al., 2007), while the updated representation of the production of O(¹D) quantitatively includes the contributions of the photodissociation of vibrationally-excited ozone and the spin-forbidden dissociation channel (Matsumi et al., 2002). HO_x chemistry plays a vital role in stabilizing CO₂ in the martian atmosphere. Fig. 1 displays a schematic of the principal pathways of the hydrogen species in the martian atmosphere with the inclusion of HOCO chemistry.

The lifetime of HOCO in Earth’s and Mars’ atmosphere is defined by:

$$\tau_{(\text{HOCO,Earth or Mars})} = \left(\frac{1}{k_2[\text{O}_2]} \right).$$

Given Mars’s small atmospheric O₂ content, pressure and temperature conditions, HOCO can be stabilized. Consequently, the lifetime of HOCO is much longer in its atmosphere (Fig. 2), ranging from 90 ns and 30 μs at the Earth’s and Mars’s surface,

respectively, to 1.2 days for Mars at 240 km. Using the HOCO reaction mechanism (Table 1), we propose two new reaction channels for converting CO to CO₂ on Mars that result from the new HOCO chemistry. Two catalytic cycles are shown below.

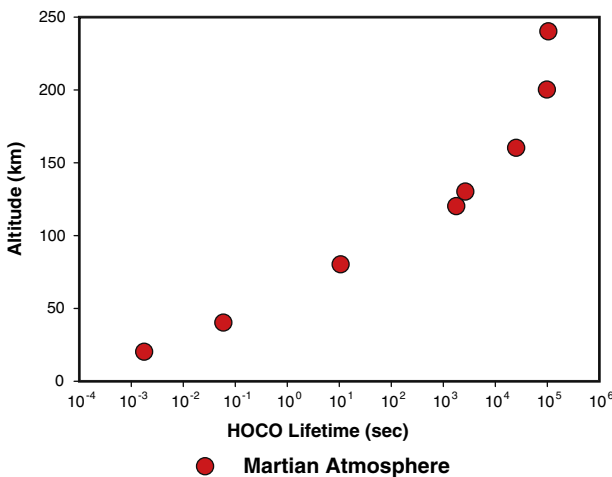


Fig. 2. HOCO lifetime (min) versus altitude (km) for and Mars.

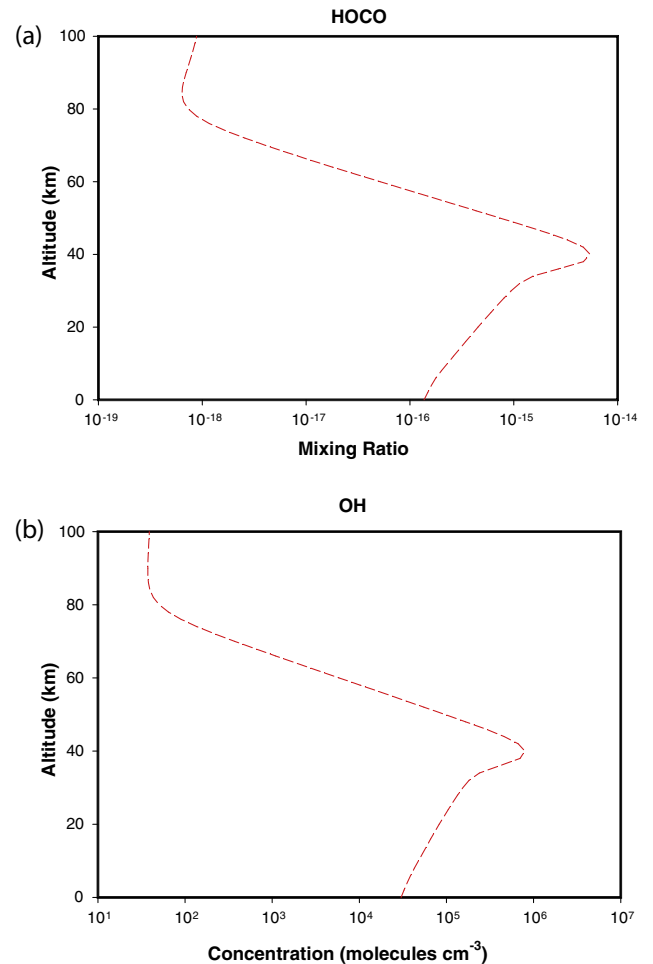


Fig. 3. (a) Altitude (km) versus HOCO mixing ratio. (b) Altitude (km) versus OH concentration.

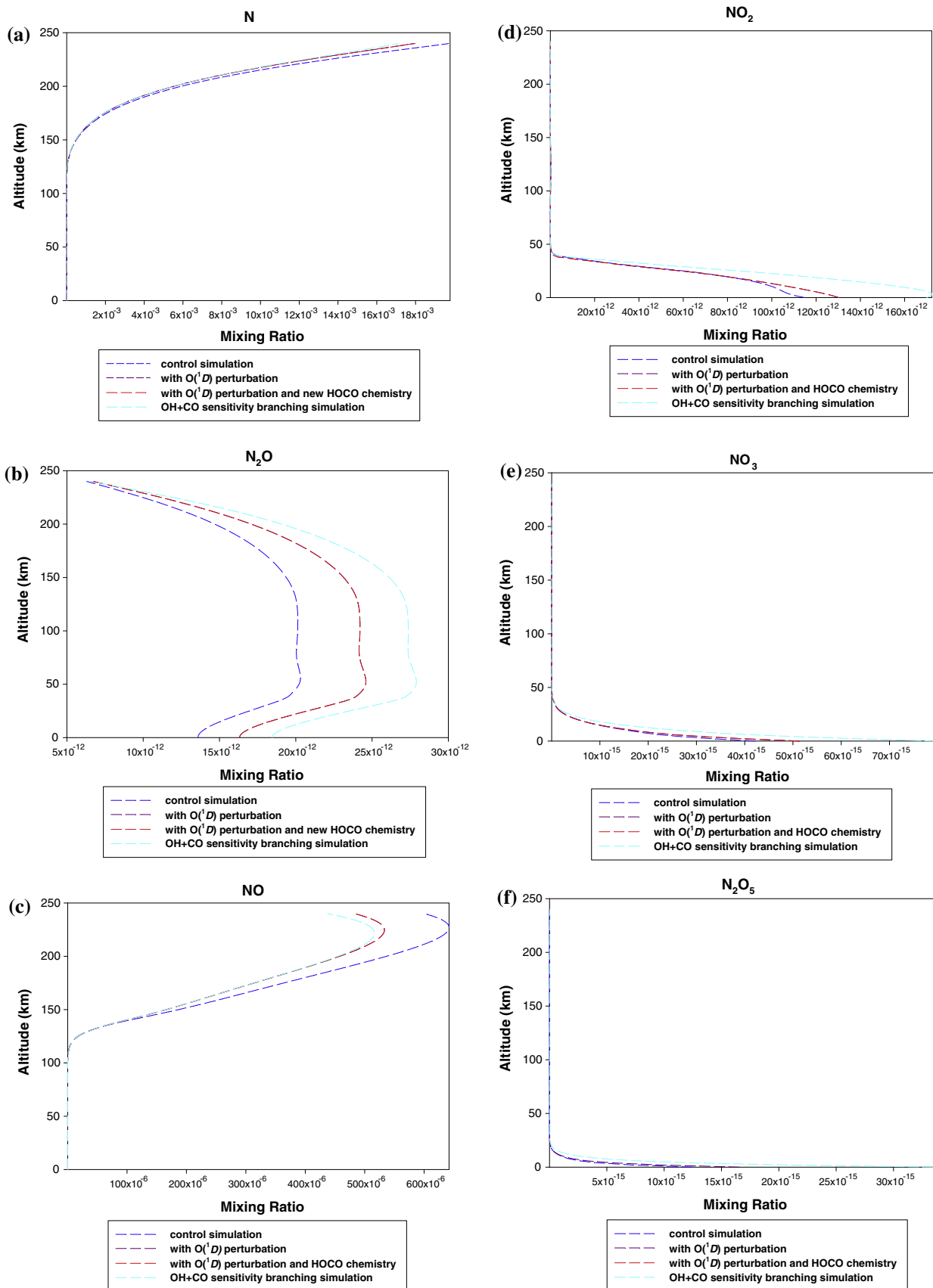


Fig. 4. (a–m) Altitude (km) versus mixing ratio plots for NO_y and HO_x species. *Note:* the OH + CO branching ratio simulation plot represents species via simulations incorporating the recent experimentally-obtained branching ratios for the oxidation of CO (Clements et al., 2002; Lu et al., 2007).

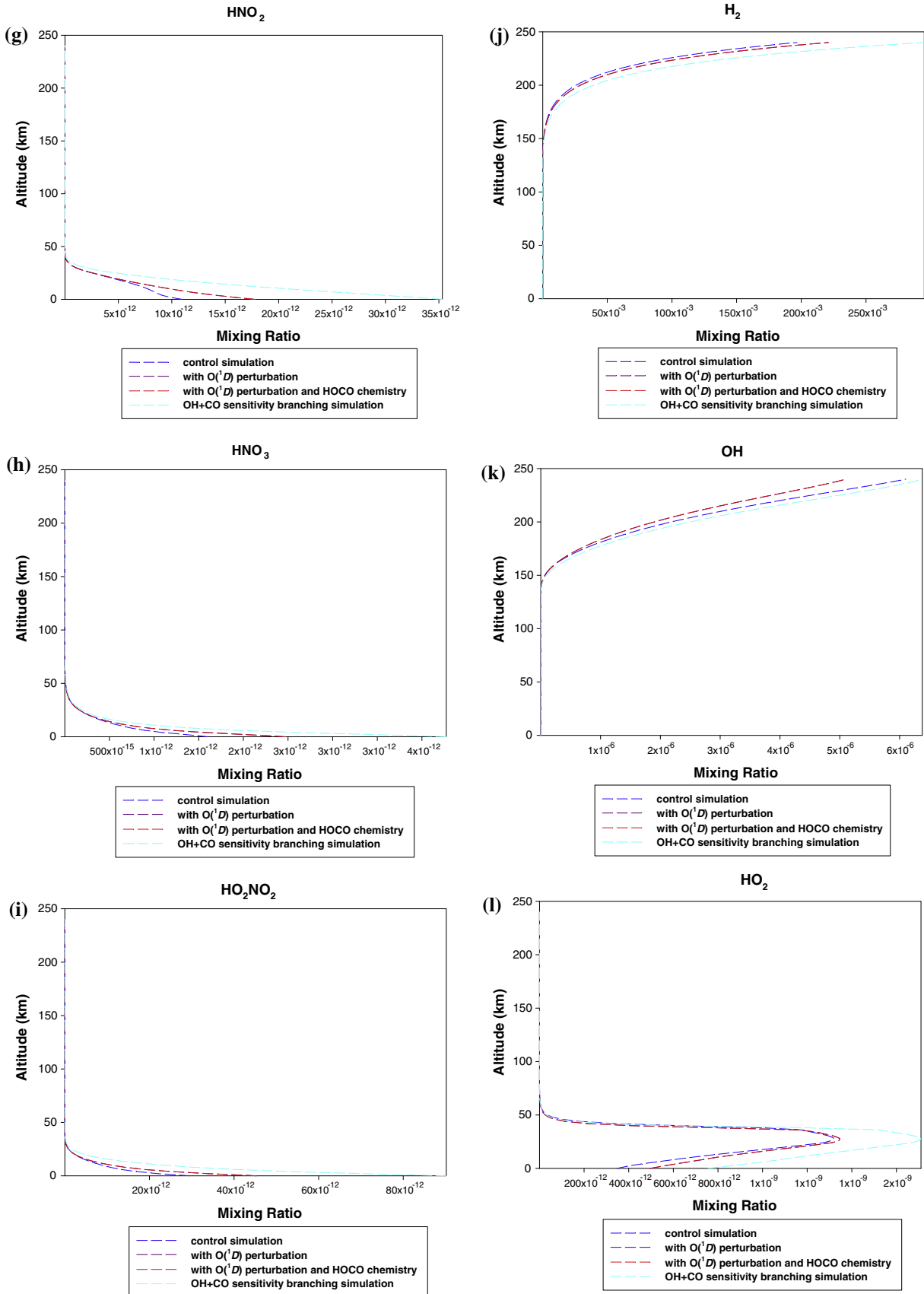


Fig. 4 (continued)

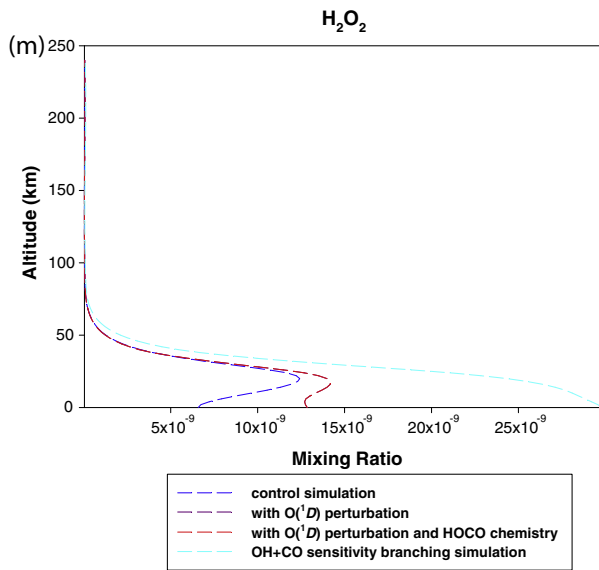
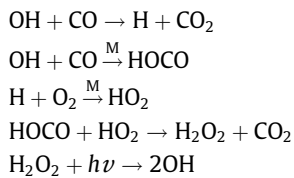
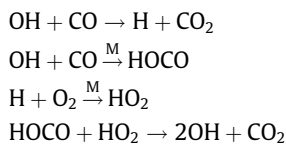


Fig. 4 (continued)



net : $2\text{CO} + \text{O}_2 \rightarrow 2\text{CO}_2$ (new catalytic cycle 1)



net : $2\text{CO} + \text{O}_2 \rightarrow 2\text{CO}_2$ (new catalytic cycle 2)

As shown in previously proposed catalytic cycles (McElroy and Donahue, 1972; Parkinson and Hunten, 1972; Yung and Demore, 1999) to convert CO to CO₂ on Mars, HO_x radicals are used as catalysts in the recombination of CO and O₂. Since HO_x radicals are not consumed in the chemical scheme, very few molecules are needed. Under martian atmospheric conditions, the production of HOCO will be governed by its low-pressure limiting rate constant (Sander et al., 2006). Fig. 3a displays a 1-D simulation of the mixing ratio of HOCO as a function of altitude. Although the loss of HOCO is dominated by its reaction with O₂, its mixing ratio profile is governed predominantly by the concentration of OH (Fig. 3b) as it is solely produced by the reaction of OH + CO + M, where 'M' (or the third body) on Mars is CO₂. Using the rate constants from Sander et al. (2006) for the reaction of OH + CO to produce H + CO₂ and HOCO, does not affect the column abundance of CO. Even though the current understanding of martian atmospheric chemistry does not fully account for CO measured from spacecraft (Rosenqvist et al., 1992; Encrenaz et al., 2006) and Earth-based (Clancy et al., 1990; Lellouch et al., 1989; Krasnopolsky, 2003, 2007) observations, our simulation of CO (200 ppmv) are in accord with recent and past measurements of CO in the martian atmosphere, which range from 200 to 1250 ppmv (Smith et al., 2009).

The primary impact of the HOCO chemistry is that it contributes, via the reaction of HCO₂ and O₂, up to 5% (at 22 km)

towards the production of CO₂. Frost et al. (1993) and Senosiain et al. (2003) represent the only experimental and theoretical study that has quantified rate constants for the OH + CO reaction under martian conditions. Yet, recent experimental and theoretically-obtained branching ratios (i.e., for HOCO and H + CO₂ via OH + CO), by Clements et al. (2002) and Lu et al. (2007) imply a factor of 8–60 increase in the HOCO total column abundance. In addition, these sensitivity simulations also reveal that HOCO may contribute 25–70% towards the production of CO₂ from the surface up to 44 and 50 km (see Supplementary material). These sensitivity simulations do not affect the concentrations of CO and CO₂, but imply that the conversion of CO to CO₂ may proceed largely through the HOCO chemical mechanism. Still, based on the current understanding of atmospheric chemistry, balancing CO₂ production and loss, has still proven to be difficult to accurately resolve (Atreya and Blamont, 1990; Atreya and Gu, 1994; Krasnopolsky, 2006). These simulations also show perturbations to column abundances of NO_y and HO_x, ranging from 15% to a factor of 3 (Fig. 4a–m).

The inclusion of an updated representation of the O(¹D) quantum yield effects NO_y, CO_x, and HO_x species, ranging from ~5% to 50% with respect to their column abundances (Figs. 4a–m, 5a and

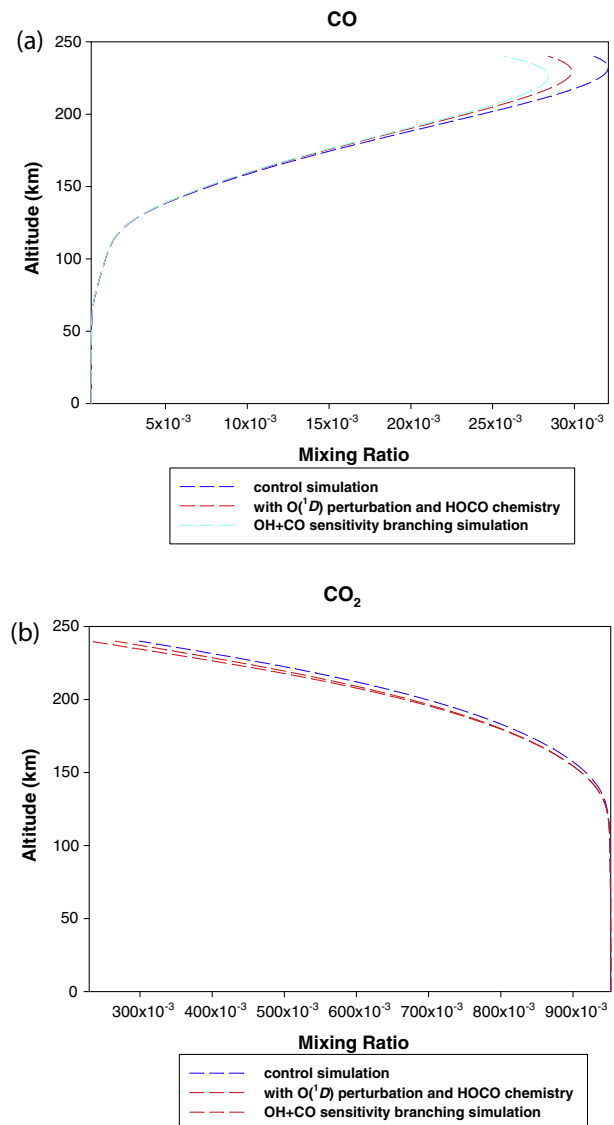


Fig. 5. (a) Altitude (km) versus CO mixing ratio. (b) Altitude (km) versus CO₂ concentration.

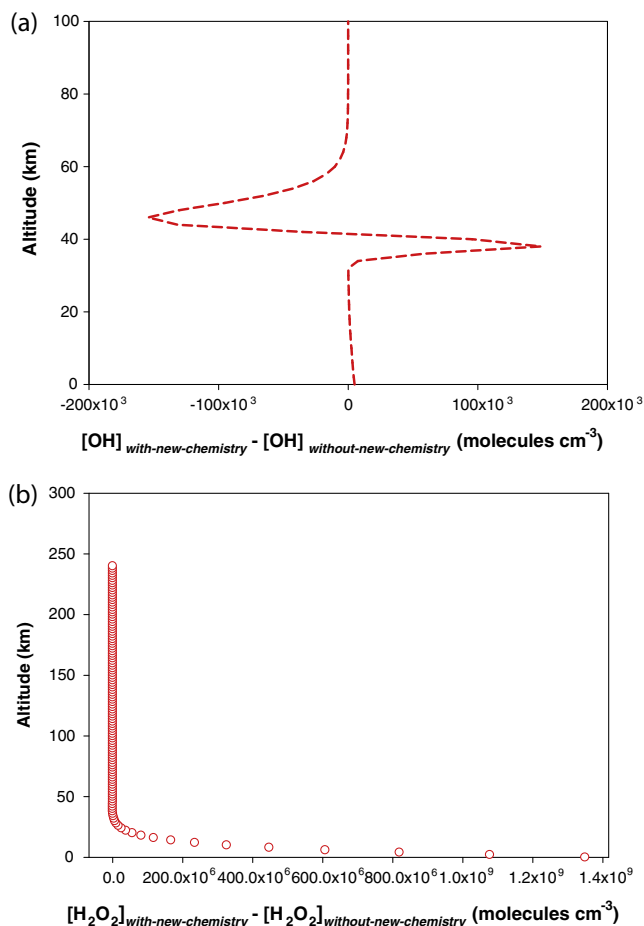


Fig. 6. (a) Altitude (km) versus $[\text{OH}]_{\text{with-new-chemistry}} - [\text{OH}]_{\text{without-new-chemistry}}$. (b) Altitude (km) versus $[\text{H}_2\text{O}_2]_{\text{with-new-chemistry}} - [\text{H}_2\text{O}_2]_{\text{without-new-chemistry}}$.

b). HO_2NO_2 exhibits the largest perturbation to its total column abundance (45% increase) of all NO_y species, which is due to increases in NO , NO_2 , NO_3 , N_2O_5 , HO_2 , HNO_3 and HNO_2 , ranging from $\sim 10\%$ to 40% . The most drastic increase in HO_x is due to a 20% increase in HO_2 , due to inclusion of the new HOCO reaction channel, $\text{HOCO} + \text{O}_2$. H_2 exhibits a 25% reduction in its column abundance. This is due to the fact that there is a reduction in the rate of H_2 formation from its primary production channel ($\text{H} + \text{HO}_2 \rightarrow \text{H}_2 + \text{O}_2$). OH and H_2O_2 exhibit 10% decrease and 50% increase, respectively, in their total column abundance (*note*: perturbations are mostly pronounced in Mars' lower atmosphere as exemplified in Fig. 6a and b). The decrease in OH is due to the production of HOCO via $\text{OH} + \text{CO} + \text{M}$, and the increase in H_2O_2 is a result of increasing contribution from the HO_2 self-reactions ($2\text{HO}_2 \rightarrow \text{H}_2\text{O}_2 + \text{O}_2$ and $2\text{HO}_2 \rightarrow \text{H}_2\text{O}_2 + \text{O}_2(^1\Delta)$). Recent Earth- and satellite-based measurements of H_2O_2 (15 ppbv) (Smith et al., 2009; Encrenaz et al., 2008) show that our simulations with the inclusion of the updated $\text{O}(^1\text{D})$ quantum yields and HOCO reaction cycles are in comparable agreement with H_2O_2 (5 ppbv).

4. Conclusions

Given the substantially longer lifetime of HOCO in Mars's atmosphere, compared to Earth, we examine the inclusion of novel HOCO chemical cycles in a 1-D photochemical model for Mars in addition to the most recent representation of the $\text{O}(^1\text{D})$ quantum yield. Our simulations, constrained by laboratory and theoretical (*i.e.*, first principle *ab initio*) rate data (Sander et al., 2006; Petty and Moore, 1993; Nair et al., 1994; Yu and Francisco, 2008)

involving HOCO and an updated representation of the $\text{O}(^1\text{D})$ quantum yield (Matsumi et al., 2002), show significant effects on Mars' atmospheric NO_y , HO_x , and CO_x chemistry and also its oxidative capacity. Similar to HO_x radicals, the HOCO chemical cycles show that H_2O_2 is more intimately linked to CO_x chemistry through the production of HOCO. The present work demonstrates that HOCO is a significant new member of the HO_x family, not previously accounted for in earlier studies of chemistry on Mars. This analysis also provides important new detection limits for target trace gas species for the ExoMars Trace Gas Orbiter Mission, scheduled for launch in 2016. Lastly, given recent advancements elucidating the importance of quantum tunneling in the $\text{OH} + \text{CO}$ reaction (regarding the loss of H from excited states of HOCO) should be further investigated via atmospheric modeling as its impact via HOCO-related chemical cycles may prove impactful (Johnson and Continetti, 2010; Johnson et al., 2011; Nguyen et al., 2012; Wang and Bowman, 2014; Wang et al., 2014).

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.icarus.2014.07.023>.

References

- Allen, M., Yung, Y.L., Waters, J.C., 1981. Vertical transport and photochemistry in the terrestrial mesosphere and lower thermosphere. *J. Geophys. Res.* 86, 3617–3627.
- Atreya, S.K., Blamont, J.E., 1990. Stability of the martian atmosphere: Possible role of heterogeneous chemistry. *Geophys. Res. Lett.* 17, 287–290.
- Atreya, S.K., Gu, Z.G., 1994. Stability of the martian atmosphere: Is heterogeneous catalysis essential? *J. Geophys. Res.* 99, 13133–13145.
- Boxe, C.S., Hand, K.P., Nealon, K.H., Yung, Y.L., Yen, A.S., Saiz-Lopez, A., 2012a. Adsorbed water and thin liquid films on Mars. *Int. J. Astrobiol.* 11 (3), 169–175.
- Boxe, C.S., Hand, K.P., Nealon, K.H., Yung, Y.L., Yen, A.S., Saiz-Lopez, A., 2012b. An active nitrogen cycle on Mars sufficient to support a subsurface biosphere. *Int. J. Astrobiol.* 11 (2), 109–115.
- Clancy, R.T., Muhleman, D.O., Berge, G.L., 1990. Global changes in the 0–70 km thermal structure of the Mars atmosphere derived from 1975 to 1989 microwave CO spectra. *J. Geophys. Res.* 95, 14543–14554.
- Clements, T.G., Continetti, R.E., Francisco, J.S., 2002. Exploring the $\text{OH} + \text{CO} \rightarrow \text{H} + \text{CO}_2$ potential surface via dissociative photodetachment of $(\text{HOCO})^-$. *J. Chem. Phys.* 117, 6478–6488.
- Encrenaz, T. et al., 2006. Seasonal variations of the martian CO over Hellas as observed by OMEGA/Mars Express. *Astron. Astrophys.* 459, 265–270.
- Encrenaz, T. et al., 2008. Simultaneous mapping of H_2O and H_2O_2 on Mars infrared high-resolution imaging spectroscopy. *Icarus* 195, 547–556.
- Frost, M.J., Sharkey, P., Smith, I.W.M., 1993. Reaction between OH (OD) radicals and CO at temperatures down to 80 K. Experiment and theory. *J. Phys. Chem.* 97, 12254–12259.
- Fulle, D., Hamann, H.F., Hippler, H., Troe, J., 1996. High pressure range of addition reactions of HO. 2. Temperature and pressure dependence of the reaction of $\text{HO} + \text{CO} \leftrightarrow \text{HOCO} \rightarrow \text{H} + \text{CO}_2$. *J. Chem. Phys.* 105, 983–1000.
- Johnson, C.J., Continetti, R.E., 2010. Dissociative photodetachment studies of cooled HOCO-anions revealing dissociation below the barrier to $\text{H} + \text{CO}_2$. *J. Phys. Chem. Lett.* 1 (12), 1895–1899.
- Johnson, C.J., Poad, B.L., Shen, B.B., Continetti, R.E., 2011. New insight into the barrier governing CO_2 formation from $\text{OH} + \text{CO}$. *J. Chem. Phys.* 134 (17), 171106. <http://dx.doi.org/10.1063/1.3589860>.
- Krasnopolsky, V.A., 2003. Spectroscopic mapping of Mars CO mixing ratio: Detection of north–south asymmetry. *J. Geophys. Res.* 108. <http://dx.doi.org/10.1029/2002JE001926>.
- Krasnopolsky, V.A., 2006. Photochemistry of the martian atmosphere: Seasonal, latitudinal, and diurnal variations. *Icarus* 185, 153–170.
- Krasnopolsky, V.A., 2007. Long-term spectroscopic observations of Mars using IRTF/CSHELL: Mapping of O_2 dayglow, CO, and search for CH_4 . *Icarus* 190, 93–102.
- Lellouch, E., Paubert, G., Encrenaz, T., 1989. Mapping of CO millimeter-wave lines in Mars' atmosphere: The spatial variability of carbon monoxide on Mars. *Planet. Space Sci.* 39, 219–224.
- Lu, Z., Hu, Q., Oakman, J.E., Continetti, R.E., 2007. Dynamics on the HOCO potential energy surface studied by dissociation photodetachment of HOCO^- and DOCO^- . *J. Chem. Phys.* 126, 194305-1–194305-11.
- Matsumi, Y., Comes, F.J., Hancock, G., Hofzumahaus, A., Hynes, A.J., Kawasaki, M., Ravishankara, A.R., 2002. Quantum yields for production of $\text{O}(^1\text{D})$ in the ultraviolet photolysis of ozone: Recommendation based on evaluation of laboratory data. *J. Geophys. Res.* 107 (D3), 4024. <http://dx.doi.org/10.1029/2001JD000510>.

- McElroy, M.B., Donahue, T.M., 1972. Stability of the martian atmosphere. *Science* 177, 986–988.
- Mielke, Z., Olbert-Majkut, A., Tokhadze, K.G., 2003. Photolysis of the OC center dot dot HONO complex in low temperature matrices: Infrared detection and ab initio calculations of nitrosoformic acid, HOC(O)NO. *J. Chem. Phys.* 118, 1364–1377.
- Nair, H., Allen, M., Anbar, A.D., Yung, Y.L., Clancy, R.T., 1994. A photochemical model of the martian atmosphere. *Icarus* 111, 124–150.
- Nguyen, T.L., Xue, B.C., Weston Jr., R.E., Barker, J.R., Stanton, John F., 2012. Reaction of HO with CO: Tunneling is indeed important. *J. Phys. Chem. Lett.*, 1549–1553. <http://dx.doi.org/10.1021/jz300443>.
- Olkhov, R.V., Li, Q., Osborne, M.C., Smith, I.W.M., 2001. Branching ratios for competing channels in the reaction HOCO radicals with NO. *Phys. Chem. Chem. Phys.* 3, 4522–4528.
- Owen, T., Biemann, K., Rushneck, D.R., Biller, J.E., Howarth, D.W., Lafleur, A.L., 1977. The composition of the atmosphere of the surface of Mars 82 (28), 4635–4639.
- Parkinson, T.D., Hunten, D.M., 1972. Spectroscopy and aeronomy of O₂ on Mars. *J. Atmos. Sci.* 29, 1380–1390.
- Petty, J.T., Moore, C.B., 1993. Transient infrared-absorption spectrum of the nu-1 fundamental trans-HOCO. *J. Mol. Spectrosc.* 161, 149–156.
- Petty, J.T., Harrison, J.A., Moore, C.B., 1993. Reactions of trans-HOCO studied by infrared-spectroscopy. *J. Phys. Chem.* 97, 11194–11198.
- Rosenqvist, J. et al., 1992. Minor constituents in the martian atmosphere from the ISM/Phobos experiment. *Icarus* 98, 254–270.
- Sander, S.P. et al., 2006. Chemical Kinetics and Photochemical Data for Use in Atmospheric Studies, Evaluation Number 15. JPL Publ. 06-2. Jet Propulsion Lab, Pasadena.
- Sears, T.J., Fawzy, W.M., Johnson, P.M., 1992. Transient diode-laser absorption-spectroscopy of the nu-2 fundamental of trans-HOCO and DOCO. *J. Chem. Phys.* 97, 3996–4007.
- Senosiain, J.P., Musgrave, C.B., Golden, D.M., 2003. Temperature and pressure dependence of the reaction of OH and CO master equation modeling on a high-level potential energy surface. *Int. J. Chem. Kinetics* 35, 464–474.
- Smith, M.D., Wolff, M.J., Clancy, R.T., Murchie, S.L., 2009. CRISM observations of water vapor and carbon monoxide. *J. Geophys. Res.* 114, E00D03. <http://dx.doi.org/10.1029/2008JE003288>.
- Wang, X., Bowman, J.M., 2014. Mode-specific tunneling in the unimolecular dissociation of cis-HOCO to H + CO₂. *J. Phys. Chem. A* 118 (4), 684–689. <http://dx.doi.org/10.1021/jp5000655>.
- Wang, J., Li, J., Ma, J., Guo, H., 2014. Full-dimensional characterization of photoelectron spectra of HOCO- and DOCO- and tunneling facilitated decay of HOCO prepared by anion photodetachment. *J. Chem. Phys.* 140, 184314. <http://dx.doi.org/10.1063/1.4874975>.
- Yu, H.G., Francisco, J.S., 2008. Energetics and kinetics of the reaction of HOCO with hydrogen atoms. *J. Chem. Phys.* 128, 244315–244315-6.
- Yu, H.G., Muckerman, J.T., Francisco, J.S., 2005. Direct ab initio dynamics study of the OH plus HOCO reaction. *J. Phys. Chem. A* 109, 5230–5236.
- Yu, H.-G., Poggi, G., Francisco, J.S., Muckerman, J.T., 2008. Energetics and molecular dynamics of the reaction of HOCO with HO₂ radicals. *J. Chem. Phys.* 129, 214307-1–214307-9.
- Yung, Y.L., Demore, W.B., 1999. *Photochemistry of Planetary Atmospheres*. Oxford Univ. Press, Oxford.
- Yung, Y.L., Wen, J.S., Pinto, J.P., Allen, M., Pierce, K.K., Paulson, S., 1988. HDO in the martian atmosphere: Implications for the abundance of crustal water. *Icarus* 76, 146–159.