WARMING EARLY MARS WITH A DENSE ATMOSPHERE OF CO_2 AND H_2: A REVIEW OF RECENT NUMERICAL AND EXPERIMENTAL ADVANCES

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Introduction: To this day, the enigma of Mars' ancient climate remains unexplained (Wordsworth et al. 2016, Haberle et al. 2017, Kite 2019). What was the atmosphere of Mars made of at the time when – near the Late Noachian epoch – lakes and valley networks (see e.g., Fassett & Head 2008a,b, Hynek et al. 2010, Goudge et al. 2015) were formed? Although there is a broad consensus to date that liquid water is the main culprit, the nature of the atmosphere at the time (i.e., the atmospheric pressure and composition) remains essentially unknown (Wordsworth et al. 2016, Haberle et al. 2017, Kite 2019).

Many hypotheses have been proposed and tested so far to warm the surface of Mars enough to keep surface water reservoirs liquid. However, none of them provide satisfactory results:

- Accumulating several bars of CO_2 – to values even higher than what is allowed by the few existing observations (see Kite 2019, Fig. 9) – into the atmosphere does not work (Forget et al. 2013, Wordsworth et al. 2013). This is because CO_2 condenses (possibly on the surface) and because the CO_2 greenhouse effect saturates above 2-3bar (for a low-gravity planet like Mars) due to the cooling by Rayleigh scattering (Wordsworth et al. 2010, Forget et al. 2013, Kopparapu et al. 2014, Ramirez et al. 2014, Turbet & Tran 2017). The greenhouse effect of the CO_2 ice clouds (Forget et al. 2013, Kitzmann 2016) and water ice clouds (Wordsworth et al. 2013, Ramirez & Kasting 2017, Turbet et al. 2020a) do not allow Mars to be heated sufficiently either.
- Accumulating volcanic gases (SO_2, H_2S) does not work, because the volcanic aerosols produce overall a net cooling effect (Tian et al. 2010, Halevy & Head 2014, Kerber et al. 2015).
- Meteoritic impacts do not work, because their cumulated impact on the hydrological cycle is too small to carve valley networks (Turbet 2018, Steakley et al. 2019, Turbet et al. 2020a).

Given the apparent failure of these hypotheses, a new hypothesis has recently emerged, according to which the warm climate of early Mars would have been sustained by a dense CO_2+H_2 atmosphere (Ramirez et al. 2014, Wordsworth et al. 2017, Turbet et al. 2020b). From a climatic point of view, a dense CO_2+H_2 atmosphere is the most favored scenario to date, as it is the only composition known to explain the apparent persistence of surface liquid water, and thus the presence of Martian valley networks and lakes, despite the reduced solar luminosity of the time (about 75% of today's). This scenario, which requires that the atmosphere and presumably the mantle of Mars have been chemically reduced in the past, has attracted considerable attention in recent years (Ramirez et al. 2014, Batalha et al. 2015, Wordsworth et al. 2017, Turbet et al. 2019, Ramirez 2019, Turbet et al. 2020b, Kamada et al. 2020, Hayworth et al. 2020, Ramirez et al. 2020, Godin et al. 2020, Turbet & Forget 2021, Wordsworth et al. 2021, Guzewich et al. 2021, Kamada et al. 2021). This has also revived interest in studying the climatic effects of large impacts that may have generated large amounts of H_2 (Haberle et al. 2019); although we recall the readers that these large impacts are not contemporaneous with the periods of lake and valley network formation (Fassett & Head 2008, 2011, Turbet et al. 2020a).

In this presentation, we will review our recent advances to test the CO_2+H_2 hypothesis. Firstly on the experimental side, to better constrain the spectral opacity of a CO_2+H_2 rich atmosphere, which determines the amount of H_2 needed to heat Mars, and thus the plausibility of this scenario. Secondly on the numerical side, to better understand the impact of a CO_2+H_2 rich atmosphere on the hydrological cycle, which can then be compared with the geologic records (e.g., maps of lakes and valley networks).

Results from laboratory experiments: We conducted a series of laboratory experiments, using the Fourier-Transform Spectroscopy (FTS) technique (Turbet et al. 2019, 2020b, Fakhardji et al. 2022) and the Cavity Ring Down Spectroscopy (CRDS) technique (Mondelain et al. 2021). Most of these experiments are part of the COMPLEAT (COntinuum Measurements for PLanEtary ATmospheres) French ANR project, which aims at better evaluating the continuum absorptions (CIA, dimer, far wings) of hybrid gas mixtures. Fig. 1 summarizes all the measurements we have made so far of the collision-induced absorption (CIA) produced by the pair CO_2+H_2. The measurements are in good agreement (see Fig. 1) with our theoretical calculations in black (Turbet et al. 2020b, Mondelain et al. 2021), at least in the 20-50µm CO_2 spectral window, where the CO_2+H_2 CIA matters the most for the greenhouse effect calculations. The agreement with measurements performed in the 2.1-2.55µm spectral region (Mondelain et al. 2021, Fakhardji et al. 2022) provide additional confidence that the calculations perform quite well.

Our calculations can be extended to a wide range of temperatures (typically from 100 to 600K), as shown in Fig. 2. The resulting look-up tables are made available to the community (Turbet et al. 2020b, Mondelain et al. 2021, Fakardhji et al. 2022), and can be directly implemented as new opacity sources in radiative transfer models.

Results from 1-D and 3-D climate model simulations: We implemented these new CO_2+H_2 opacity sources in our early Mars 1-D and 3D climate models (using the LMD 3-D Generic Global Climate Model – GCM). We first evaluated – following Ramirez et al. 2014, Wordsworth et al. 2017, Turbet et al. 2020b – how the mean surface temperature of early Mars evolves as a function of CO_2 and H_2 atmospheric reservoirs, as illustrated in Fig. 3 (taken from Turbet & Forget 2021). With our 1-D radiative-convective climate model calculations (Turbet et al. 2020b), we find that the amount of H_2 required to warm early Mars is about 7% (for 2 bar of CO_2), i.e. between the previous results of Ramirez et al. 2014 (15 %) and Wordsworth et al. 2017 (2.5 %), as illustrated in Fig. 3 (black, pink and green data points). We further constrain these numbers using 3-D Global Climate Model simulations (see Fig. 3; red, blue and orange data points) assuming different surface water reservoirs (Turbet & Forget et al. 2021).

More importantly, we explored the impact of a dense CO_2+H_2 atmosphere on the hydrological cycle, for different CO_2 surface pressures (1 and 2 bar), H_2 mixing ratios (from 0.5 to 30%), and water reservoir distributions (see Fig. 3, maps on the left), assuming a 40° obliquity. We find that the adiabatic cooling mechanism (Wordsworth et al., 2013) that leads to the preferential accumulation of ice deposits in the southern highlands in cold climates (the so-called 'icy highland' scenario) also works in warm climates, with impact crater lakes acting as the main water reservoirs. This produces rainfall localized in the southern highlands of Mars (see an example in Fig. 4), whether oceans are present or not. Fig. 4 illustrates that the observed distribution of valley networks can match – with a few exceptions detailed in Turbet & Forget 2021 – the observed distribution of valley networks and impact crater lakes.

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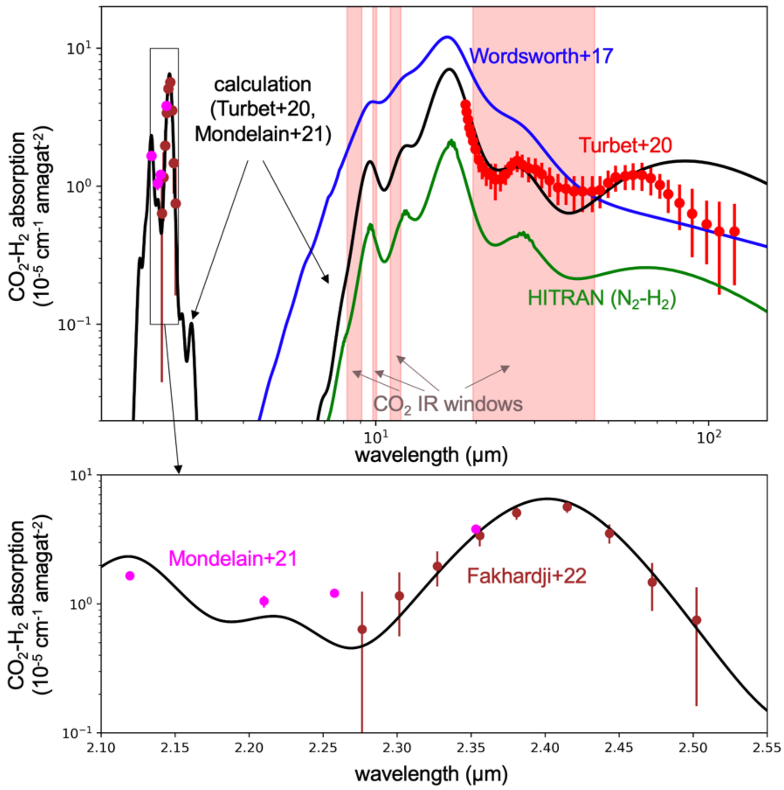

Figure 1 – CO_2-H_2 collision-induced absorption (in units of 10^{-5} cm^{-1} amagat^{-2}) as a function of wavelength (in micron units), and at 296K. The upper panel gives a global representation, while the lower panel offers a zoom in the 2.1-2.55 µm spectral region. The black line corresponds to a semi-empirical calculation (Turbet et al. 2020b, Mondelain et al. 2021). Laboratory measurements are taken from Turbet et al. 2020b (in red), Mondelain et al. 2021 (in magenta) and Fakhardji et al. 2022 (in brown). For reference, we added the N_2-H_2 CIA from HITRAN (used in Ramirez et al. 2014) and the CO_2-H_2 CIA calculated in Wordsworth et al. 2017. We also added the rough locations of the main CO_2 infrared windows. We did not add the measurements of Godin et al. 2020 which exhibit much larger error bars.

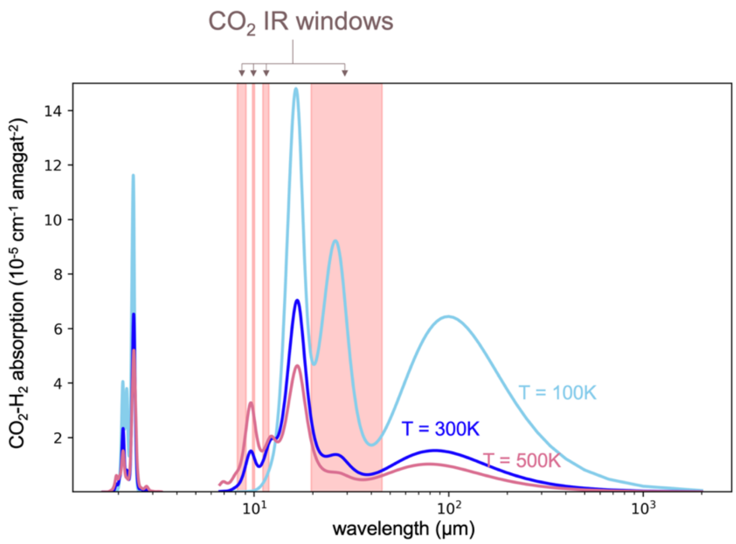

Figure 2 - CO_2-H_2 collision-induced absorption (in units of 10^{-5} cm^{-1} amagat^{-2}) as a function of wavelength (in micron units), and calculated for different temperatures (100, 300 and 500K). For reference, we added the rough locations of the main CO_2 infrared windows.

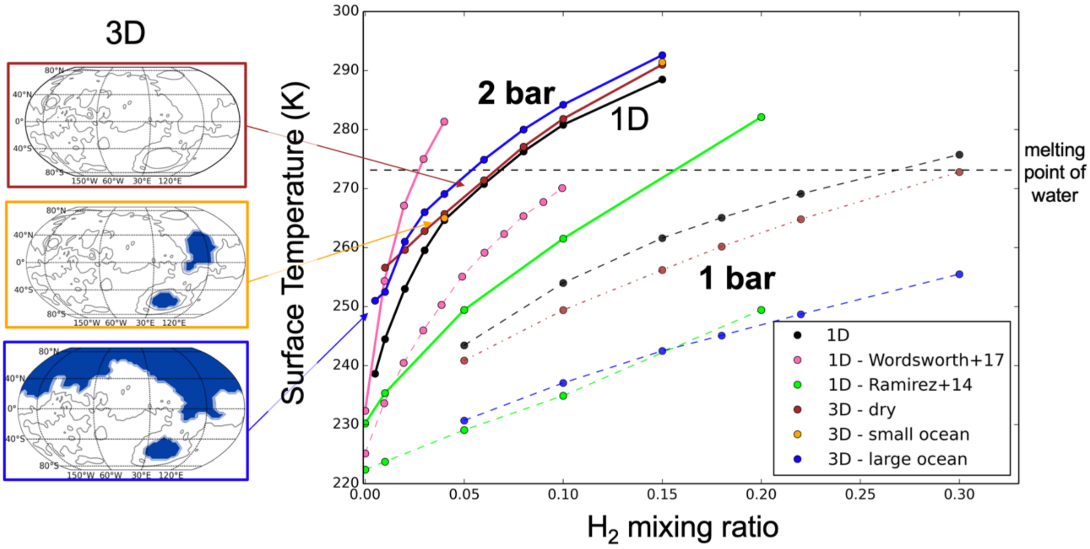

Figure 3 - Annual global mean surface temperatures (K) as a function of H_2 mixing ratio, for two different CO_2 partial pressures (solid lines = 2 bar; dashed lines =1 bar), and four different types of simulations. These include 1-D simulations (black) based on Turbet et al. (2020b), 3-D simulations from Turbet & Forget 2021 assuming a dry (i.e., low water content) planet (brown), a planet with a small 100 m GEL ocean (orange), and a planet with a large 550 m ocean (blue). For reference, we also added the 1-D results from Ramirez et al. 2014 (green) and Wordsworth et al. 2017 (pink).

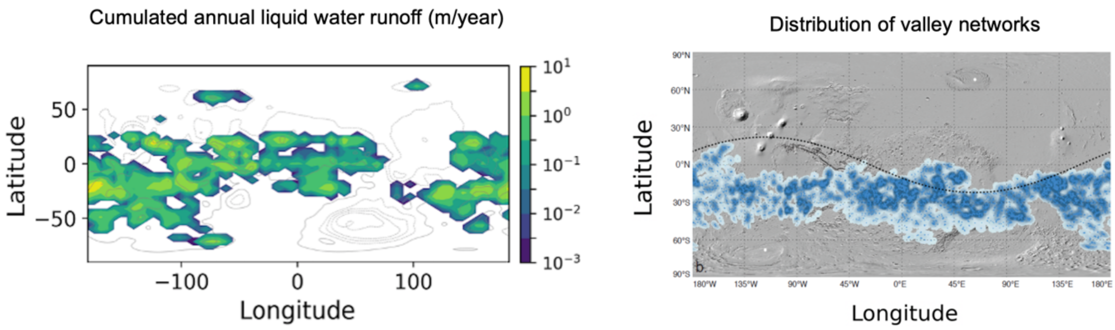

Figure 4 – On left, map of the cumulated annual liquid water runoff (Turbet & Forget 2021) calculated for a dense CO_2+H_2 atmosphere (2bar of CO_2, 15% of H_2). In this simulation, almost the entire water reservoir (a few meters global equivalent layer) is trapped in liquid form in the impact crater lakes, due to the (warm) adiabatic cooling effect (Turbet & Forget 2021). On right, map of the observed distribution of valley networks (Bouley et. al. 2016). Both maps were computed using the pre-True Polar Wander (TPW) topography of Bouley et al. 2016 (present-day topography, but without Tharsis and all the younger volcanic features; and with a 20° TPW rotation).