NUMERICAL SIMULATIONS OF THE EVOLUTION OF THE CO_2 ATMOSPHERE OF MARS: 4.53 GA TO THE PRESENT. C. V. Manning, *Department of Astronomy, U. C. Berkeley, CA 94720-3411, (cmanning@astro.berkeley.edu)*, C. P. McKay, K. J. Zahnle, *Space Science Division, NASA-Ames, Moffett Field, CA 94035*.

In this paper we approach four key questions that are central to our understanding of the nature of climate change on Mars,

- By what mechanism has the evolution of the CO_2 atmosphere, dominated at early times by violent processes, been guided to the moderate quantities present today?
- How do obliquity cycles affect the migration of CO_2 between the various reservoirs of CO_2, and what effect does this have on the bulk atmosphere of the planet in time?
- Is the geophysical evidence that the last few Myr experienced periods that are substantially wetter than the present (eg, [8, 2, 1, 3]) attributable to a substantially more massive greenhouse atmosphere?
- Is the current atmospheric pressure determined primarily by the partial pressure of CO_2 in cold (~ 148 K) ice caps [12], or is it because disequilibrium water, and hence weathering, ceases at pressures below the triple point of water [10]?

We approach these problems by assembling a detailed numerical model of the bulk atmosphere of Mars, incorporating functional representations of every source, sink, and reservoir of CO_2 we have found in the literature, or have thought of ourselves, within a physically realistic picture of evolving insolation, EUV flux, and obliquity variation.

The reservoirs we track are,

$$M_{tot} = M_g + M_{fr} + M_{ads} + M_{fix},$$

the gas mass, frozen CO_2, adsorbed, and fixed as carbonates, respectively. The atmosphere mediates all changes between reservoirs. We keep track of the following atmospheric sources and sinks;

$$\frac{dm_g}{dt} = \left(\frac{dm}{dt}\right)_{dec} + \left(\frac{dm}{dt}\right)_{volc} + \left(\frac{dm}{dt}\right)_{atm} + \left(\frac{dm}{dt}\right)_{imp} + \left(\frac{dm}{dt}\right)_{ads} + \left(\frac{dm}{dt}\right)_{fr} + \left(\frac{dm}{dt}\right)_{fix};$$

thermal decomposition at depth of carbonates, volcanic outgassing of lava, atmospheric sputtering and photochemical losses, impact erosion, gas adsorbed to the regolith, CO_2 frozen at the poles, and fixed carbon.

The first three terms are independent of pressure and temperature:

⋄ We initially use the Carr method [4] of calculating the rate of burial by lava, which asserts that a fixed fraction of the total heat transport is carried by convection ($f_{convec} = 0.15$). Because of the lack of plate tectonics and the thickness of the lithosphere, we have also introduced an (arbitrary) exponential decline,

$$f_{convec} = 0.15\, e^{-t/\tau},$$

where τ is on order 1300 Myr. Carbonates buried below a depth at which the temperature is 950 K are returned to the atmosphere.

⋄ The lava produced by volcanism is a source of volatiles, though to our knowledge this source has not previously been factored into simulations. We use the average gas mass fraction of carbon oxides noted by [6], $f_g \simeq 1.7 \times 10^{-4}$. The volumentric rate of lava production is calculated directly from the convective heat transport using Carr's argument [4].

⋄ Sputtering and photochemical losses are estimated using [13], where the variation of the EUV flux with time is approximated with a power law representation from [17]. The sputtering component is given an arbitrary exponential damping $(1 - e^{-t/\tau})$ at early times with a time scale of $\tau \simeq 500$ Myr, to allow for a geomagnetic field at early times

The next four terms are pressure and/or temperature sensitive. We assume the solar flux, in units of the current flux, has increased linearly from a value of 0.7 to 1.0 over the last 4.6 Gyr. The mean planetary temperature is based on the Pollack [16] greenhouse model, but we use the analytical fit of McKay et al. [15]. We discuss pressure/temperature-dependent fluxes in order below.

⋄ We follow Melosh & Vickery [14] for impact losses and gains, but allow that the minimum mass that causes the erosion of the atmosphere above the tangent plane may exceed the mass above the tangent plane by on order a few, to account for subsequent analyses that suggest impact erosion is less efficient.

⋄ The mass of CO_2 adsorbed to the regolith is represented in a form consistent with [7],

$$M_{ads} = C_{ads}\, e^{-T_{mean}/T_d}\, P^{\gamma},$$

where we follow [15] in assuming $T_d = 35$ K, $\gamma = 0.275$ and M_{ads} is consistent with 300 mbar at the present time. We assume the regolith comes into equilibrium with the atmosphere on a time-scale of ~ 3000 yr.

⋄ To determine whether CO_2 will freeze, one needs an equation to model the meridional transport of energy to the poles. We adopt the following form,

$$T_{pole} = T_{eq-pole} + (T_{mean} - T_{eq-pole}) \left(\frac{2}{\pi}\right) \tan^{-1}(P/P_{scl})^{\beta}$$

T_{mean} is the surface area-weighted mean temperature, using the Hoffert insolation model [9], which estimates average annual insolation as a function of latitude. $T_{eq-pole}$ is the weighted temperature based on the insolation model applied to the polar cap only (albedo ~ 0.7). When $P_{scl} = 160$ mbar and $\beta = 0.7$, the present pole temperature is reproduced (at obliquity $\delta = 25.2°$), and also results in a transition to a greenhouse environment when $\delta \gtrsim 27.5°$, as implied by [9]. The above arc tangent function replaces an exponential form used in [15]. This alteration helps to maintain a modest difference between T_{pole} and T_{mean} even at high pressures, but returns $T_{eq-pole}$ when pressures are very small.

$\diamond$ We use the Pollack [16] weathering model, though we also incorporate Carr's [4] restriction that the parameter g_3, which represents the temperature dependency of the weathering rate, is multiplied by a factor that declines linearly from 1.0 to 0.01 for temperatures between 273 to 250 K, respectively.

Our program uses the Laskar et al. obliquity and eccentricity data [11] as input for the planetary insolation calculations. This data is presented for each 500 year step over the last 10 Myr. We assume, moreover, that these variations are characteristic of the changes during 10 Myr periods during the entire last 4.6 Gyr, and that we can apply the data to the past without a loss of generality. That is, we assume that the sense of the evolution of the atmosphere is not lost if the specific timing of obliquity variations is lost. The trends of obliquity suggest that a complete cycle of 20 Myr can be made by inverting the data and adding it to an uninverted copy. Such a 10 Myr cycle is shown in Fig. 1.

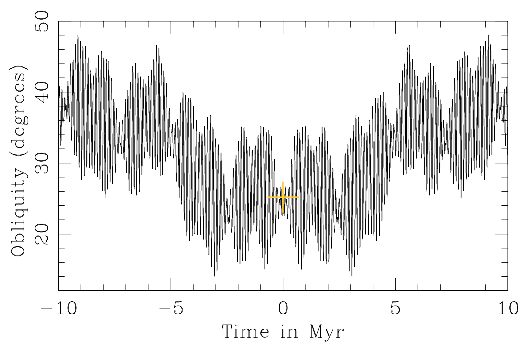

Figure 1: The Laskar obliquity data [11] (from 0 to −10 Myr), mirrored into the future, to give the semblance of a complete obliquity cycle. The plus sign represents the present conditions. See text for the rationalè for using this data as characteristic of obliquity variations in the past.

Illustrative Results: Fig. 2 shows the variation of the various CO_2 reservoirs in the very early Noachian, when the starting total is 2.5 bar. The atmosphere is seen to fluctuate between a runaway "greenhouse" phase and an "ice-house" phase. During the ice-house, the ice-cap is the largest reservoir, and in a greenhouse phase most CO_2 is in the regolith. The downward tilt in the pressure during greenhouse phases is due primarily to impact erosion, somewhat moderated at early times by thermal decomposition of carbonates. The carbonates initially placed in the regolith are being buried rapidly by lava and thermally decompose at depth. Fig. 3 shows the entirety of the Noachian period, where the ice-cap mass is removed for clarity. In this example, the atmosphere comes to a minimum at about 4.1 Ga, then gradually begins to build up. Note the rough correspondence of the cumulative impact erosion and outgassing from lava.

These early results suggest an answer to the first key question posed at the outset. Due to the nature of impact erosion, which is more effective when the atmosphere is in greenhouse

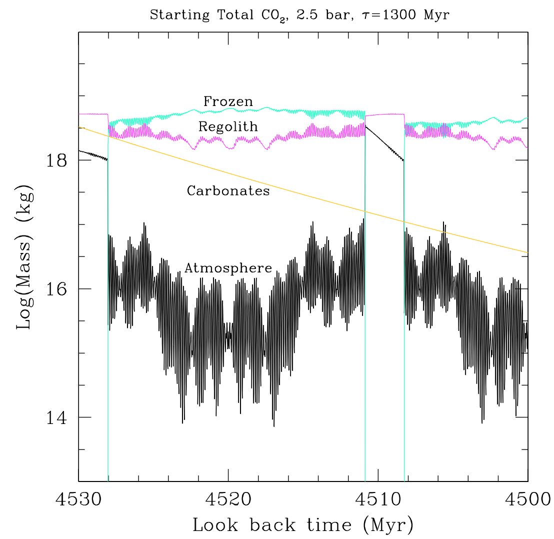

Figure 2: An early Noachian simulation showing the trend in the four reservoirs using an initial total reservoir of 2.5 bar of CO_2, in which 1/3 is carbonates in the crust, and the balance is distributed in equilibrium between the regolith and the atmosphere.

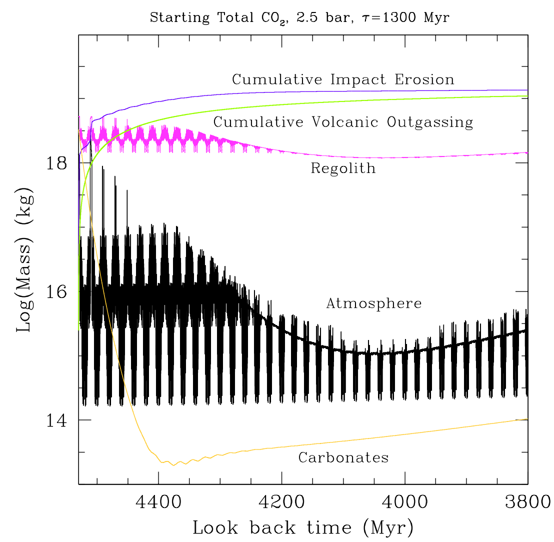

Figure 3: Same as Fig. 2 but including the entire Noachian, but where the frozen CO_2 has been omitted for clarity. We show the cumulative impact erosion and the cumulative volcanic outgassing. Impact erosion can be seen to increase in "spurts" during greenhous phases.

mode, there is a natural dynamic balance of the atmospheric pressure between the erosive effects of impacts and outgassing of CO_2 *if* outgassing rates are greater than the combined loss rates from sputtering, photochemical losses, and weathering.

The obliquity cycles in Fig. 2 (reflected by variations in atmospheric pressure during the ice-house phase) are shown to have a profound effect on variations in the atmosphere. Simulations show that the larger the amount of CO_2 placed in the reservoirs, the larger the fraction of time the atmosphere will be in the greenhouse phase. However the impact erosion rate is so high at early Noachian times that the atmosphere is quickly eroded to just a few mbar, at which point the distinction between ice-house and greenhouse is negligible.

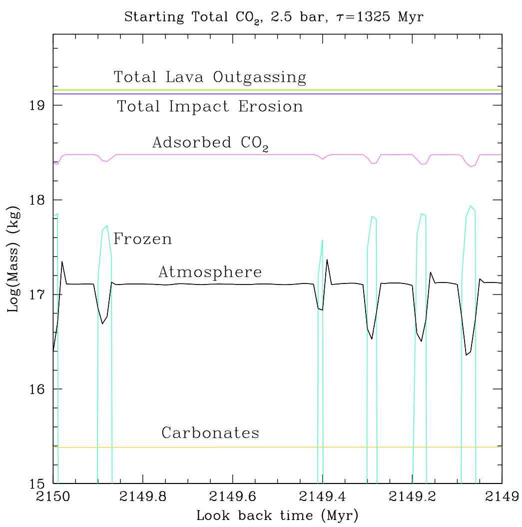

Figure 4: A high obliquity phase in the Hesperian showing the trend of various reservoirs in time. Even in the Hesperian, impact erosion appears able to significantly erode a greenhouse atmosphere. The cumulative outgassing from lava is almost equal to the total impact erosion. The atmospheric pressure at 2149.5 Ma is ~ 34 mbar.

Figures 4 and 5 show the reservoirs, and sources and sinks to the atmosphere, respectively, for a mid to late Hesperian high-obliquity period. Figure 4 shows the log of the mass as a function of time, while Fig. 5 shows the log of the mass change per Myr for various terms. This simulation shows the source, lava outgassing, exceeds impact erosion, sputtering and weathering. In this case, the sum of the sources slightly exceed that of the sinks.

Recent observations are suggest of the existence of a very recent former ice cap [8], of recent lacustrine environments [2], of very recent floods in Athabasca Valles which experienced a gradual decline in flow [1]. These, and the sightings of snow packs on pole-facing slopes [5], and ice and rock glackers, and terrestrial mudflows [3], all suggest that the environment in the recent past was warmer and wetter than it is at present. Is this attributable to a more massive greenhouse atmosphere? Figure 6 shows one the results of a simulation which placed 0.53 bar

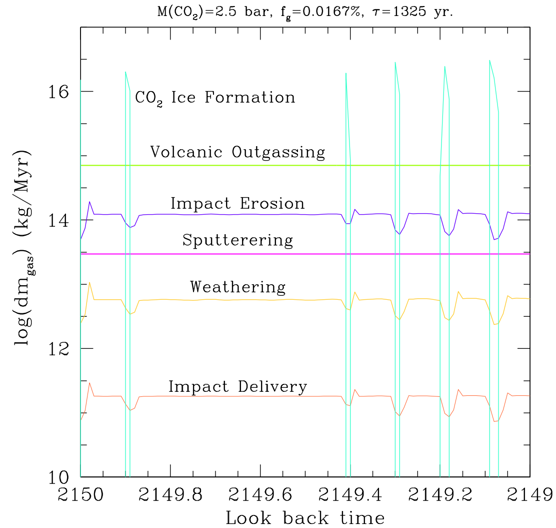

Figure 5: Same time period as Fig. 4, but represents the rate of change of sources or sinks for the atmosphere. The largest source is lava outgassing, while the sinks, impact erosion, sputtering and weathering, come close to balancing this source. Note that CO_2 moves between ice caps and the regolith, mediated by the atmosphere. The thermal decomposition of carbonates is negligible at this epoch.

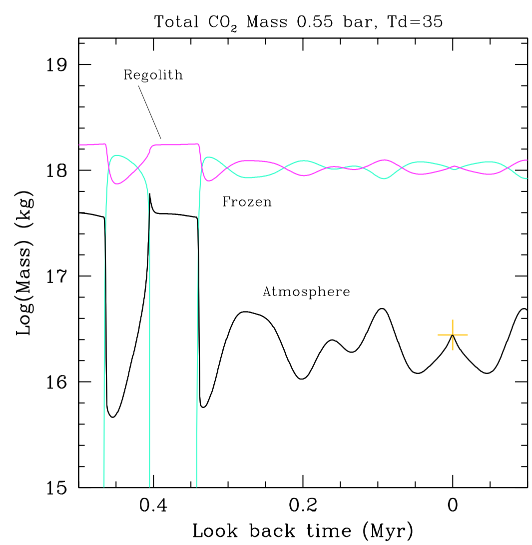

Figure 6: The possible variation of CO_2 reservoirs at very recent times. A total reservoir of 2.18×10^{18} kg was used.

(2.18×10^{18} kg) at 10 Ma, distributed in equilibrium between the ice-cap, the regolith and the atmosphere. It shows that the most recent obliquity variations (within the last 0.5 Myr) result in a runaway greenhouse $\sim 350,000$ yr ago, with an atmospheric pressure of ~ 100 mbar. The mean temperature of Mars would then have been on order 10 C higher than at present. At high obliquity, the temperature rise at mid- to high-latitudes is significantly greater than this.

These simulations seem to support a Leighton and Murray model [12] in which the partial pressure of CO_2 at the coldest pole determines the atmospheric pressure, although it is essentially by construction, since meridional transport is designed to be consistent with the current pole temperature and planetary pressure. But is the Kahn mechanism [10] also possible? If so, then weathering as a sink must dominate outgassing as a source, and the atmosphere must be evolving from a much higher pressure than the present so that the greenhouse effect will surpress ice-cap formation and accelerate weathering. This would appear to require that impact erosion was ineffective at early times. It would also appear to require that the current CO_2 ice-cap mass is negligible. While no direct measurement can disprove this at present, if the CO_2 ice cap *is* small, then it may be difficult to explain the presence of recent snow-fields, glaciers and mud flows in the highlands of the southern hemisphere, for a larger obliquity at the current pressure would do very little to the mean temperature or the water-carrying capacity of the atmosphere.

Simulation as a Tool: Beyond the present effort to model the evolution of the CO_2 atmosphere, the present model can be enhanced to study the effects of the temperature and pressure fluctuations on the evaporation rate of water and on the holding capacity of the atmosphere, required to estimate precipitation rates.

The rate of fractionation of isotopes is dependent on their fractional presence in the atmosphere near the exosphere. Ice-house phases will leave noble gases and nitrogen exposed to greater rates of sputtering losses. On the other hand greenhouse phases tend to protect these gases from fractionation. Thus the extent to which fraction has proceeded is a measure of the fraction of time in which the atmosphere has been in ice-house phase.

Discussion: While the uncertainty in each parameter, source or sink may be large, we would suggest that the atmosphere was "guided" to its current state by various "coincidences" of parameter values, rather than its being a highly improbable state resulting from a unstable or chaotic process. That is, certain relationships betweeen sources and sinks existed at various times – such as, for instance, that outgassing dominated weathering and sputtering in the Noachian and the early Hesperian so that a stable balance with impact erosion is possible. Weathering may in principle provide another stabilizing mechanism to outgassing. Perhaps a more sophisticated analysis of weathering rates would suggest a more dominating effect, especially at late times. In any case, a broader "phase space" should be searched for possible configurations that could explain the present "end-point".

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