MARS VOLATILES, CLIMATE, AND HABITABILITY: HISTORY AND INVENTORY OF CO_2 AND H_2O. B.M. Jakosky, LASP and Geological Sciences, University of Colorado, 3665 Discovery Dr., Boulder, CO 80303 (bruce.jakosky@lasp.colorado.edu).

Introduction: We use spacecraft measurements to determine the inventory of CO_2 gas on Mars. We estimate the amounts of gas from an early, thicker Martian atmosphere that have been lost to space by impact ejection and by solar and solar-wind stripping, and that have been removed to non-atmospheric reservoirs of CO_2 ice, clathrate hydrate, adsorbed gas, or carbonate minerals. Loss to space has removed 1-2 bars of CO_2. Deeply buried carbonates may contain up to the equivalent of a bar of CO_2, with the other sinks likely contain no more than ~90 mbar of CO_2. These sinks can readily account for loss of the bulk of an early CO_2 atmosphere thought to have been necessary to provide early greenhouse warming. Loss of CO_2 from the atmosphere to these sinks is the likely explanation for the transition in climate from an early, warmer atmosphere to the cold, dry atmosphere that has been present since early in the Hesperian epoch.

Approach: Our goal is to identify from observations where the CO_2 from an early atmosphere went, to determine whether the identifiable sinks for CO_2 can account for loss of a thicker early atmosphere, and to see if removal of CO_2 into non-atmospheric sinks can explain, at least in part, the transition inferred for the Martian climate.

Sources and sinks for CO_2: We consider the following sources and sinks:

- Supply during accretion, including later impacts.
- Supply by release from intrusive and extrusive volcanic eruptions.
- Loss by ejection to space by impact.
- Loss by solar and solar-wind stripping.
- Formation of CO_2 ice or clathrate in the polar caps or high-latitude subsurface.
- Formation of carbonate minerals in the shallow subsurface.
- Formation of carbonate minerals in the deep subsurface.
- CO_2 gas adsorbed on mineral grains in the regolith or crust.

Table 1 and Figure 1 summarize the current best estimates of the amount of gas that has been sequestered into each of the sinks. Information comes from a combination of observations of surface and subsurface composition, stability analysis based on composition and temperature, observations of loss to space and extrapolation to loss through time (including use of ratios of stable isotopes as constraints on efficacy of loss), and models of loss processes:

Impact ejection to space. Models of the amounts of gas ejected to space by an impact, constrained by the observed distribution of impact craters with time since the onset of the geological record.

Stripped to space. Observations from MAVEN of the loss to space occurring at the present epoch, with loss processes extrapolated back in time as constrained by scenarios of the solar history based on observations of sun-like stars and by ratios of light stable isotopes.

Polar ice. Amounts of CO_2 ice in the south polar cap as inferred from radar observations of dense ice.

Polar/regolith clathrate. Potential abundance based on inferred/derived temperatures and stability analysis.

Near-surface carbonates. Abundance of carbonates derived for airborne dust plus global distribution of dust, and carbonates exposed at the surface in discrete locations (such as Nili Fossae).

Adsorbed gas. Abundance based on laboratory adsorption measurements plus distribution of particulate material.

Deep-crust carbonates. Carbonates observed in central peaks of impact craters and inferred to have been deposited prior to impact, plus inferred global distribution.

CO_2 Reservoir	Amount (mbar equiv.)
Impact ejection to space	500-1000?
Stripped to space	1000-2000
Polar ice	6
Polar/regolith clathrate	<30
Near-Surface Carbonates	14
Adsorbed gas	~35
(Deep-crust carbonates)	10-1000?
Total CO_2 Accounted For	~1.5-3+ bars

Table 1. Summary of amounts of CO_2 lost to the different sinks for gas.

Discussion and conclusions: Clearly, there is considerable uncertainty both in the amount of CO_2 present early on Mars and in its atmosphere and in its eventual fate. A large part of the uncertainty is inherent in the individual measurements and models. Some of the models describe a fraction of the gas that has been removed, and others describe an absolute amount (e.g., in grams or equivalent atmospheric pressure of gas). In addition, many of the analyses require extrapolation of

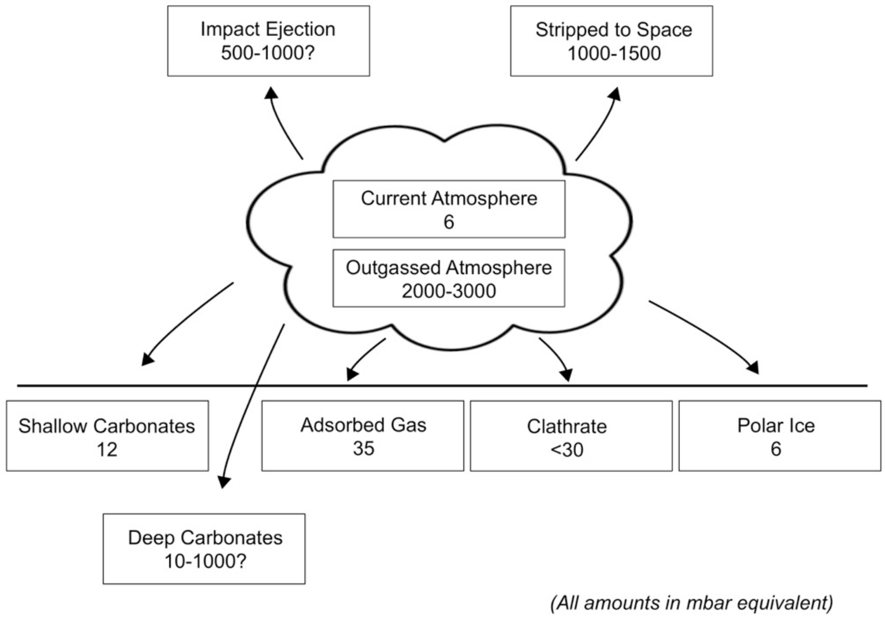

Figure 1. Graphic summary of amounts of CO_2 lost to the various sinks and reservoirs. Details are the same as in Table 1.

local measurements or processes to global behavior; definitive answers will require more investigation of the different sinks for CO_2. While additional data might be expected to change some of the results presented here, these results represent our current best estimate as to the available CO_2 and its eventual fate.

One conclusion that stands out very clearly is that the identifiable sinks for CO_2 can account for loss of a considerable amount of CO_2 from an early, thicker atmosphere. An early CO_2 atmosphere of up to several bars pressure can be accounted for by these loss processes. Of this, the largest fraction likely has been lost to space, accounting for as much as 2 bars from an early several-bar atmosphere. Even taking the lower end of the ranges for loss by impact ejection and solar/solar-wind-driven loss, loss to space accounts for loss of a bar or more of gas.

The largest sink for CO_2 that remains on the planet is likely to be deeply buried carbonates, at depths of 5-10 km below the surface. Although the amount of CO_2 locked up in deep carbonates is uncertain by a large factor, this sink may be able to account for up to an additional bar of gas.

The remaining sinks for CO_2 – polar ice, clathrate hydrate, shallow or near-surface carbonates, and adsorbed gas – likely cannot account for more than ~90 mbar of CO_2. This relatively small amount of CO_2, were it all in the atmosphere, would produce less than about 10 K of greenhouse warming. By itself, this could not have been a major contributor to early greenhouse warming.

In summary, the identifiable sinks can account for as much as several bars of CO_2 gas from an early atmosphere. This amount of CO_2 is large enough for CO_2-induced greenhouse warming to have been a significant contributor to producing temperatures capable of sustaining liquid water. The loss of CO2 from the early atmosphere into the identifiable sinks likely accounts for the transition in climate inferred from the geological constraints.