**CAN MARS BE TERRAFORMED?** B. M. Jakosky[1] and C. S. Edwards[2], [1]Laboratory for Atmospheric and Space Physics, Univ. of Colorado, Boulder, CO 30303 (bruce.jakosky@lasp.colorado.edu), [2]Dept. of Physics and Astronomy, Northern Arizona Univ., Flagstaff, AZ 86011.

**Introduction:** The potential to have human missions to Mars in the near term and large-scale or colonization missions in the far term raises the question of whether Mars can be terraformed. "Terraforming" has a wide range of possible meanings, ranging from raising the pressure and temperature enough to allow intermittent liquid water and possible plant growth, to increasing the pressure and temperature so that humans could work outside requiring only breathing apparatus to provide oxygen [e.g., 1].

Any climate change induced in the near term is likely to be driven by greenhouse warming produced by an increase in atmospheric $CO_2$ and a consequent increase in atmospheric water vapor. These two gases are the only likely sources of greenhouse warming that are available in large quantities in the Mars environment [2]. We explore the questions of how much $CO_2$ is available on Mars today, including atmospheric, polar, and surface/subsurface reservoirs, and whether it could be emplaced into the atmosphere.

This discussion is being driven by new information that was not available at the time of the analysis by McKay et al. [1] Recent analyses include (i) the dearth of carbon-bearing minerals that could retain a substantial quantity of $CO_2$ [3], (ii) the limited polar-ice deposits of $CO_2$ now thought to exist [4], and (iii) the evidence that much of an earlier, thicker atmosphere has been lost to space and is no longer available on the planet [5].

**CO2 Reservoirs:** We consider each of the possible reservoirs or sinks that could contain $CO_2$.

*Atmospheric $CO_2$.* The present-day atmosphere contains about 6 mbar atmospheric pressure, with the bulk of it being $CO_2$. This is equivalent to about 15 $g/cm^2$ above the surface.

*Polar ice.* Radar properties of the south polar layered deposits have been observed and have identified areas that are most consistent with clean and buried $CO_2$ ice. If all of this $CO_2$ were put into the atmosphere, it would roughly double the current atmospheric pressure [4].

*Carbonate minerals.* Carbonates have been identified only in small quantities, and the long-searched-for carbonate reservoir that could contain the $CO_2$ from an early thick atmosphere has not been identified. Recent analysis puts the total $CO_2$ content of carbonates at less than the equivalent of 50 mbar [3]. While there could be buried carbonates in substantial reservoirs that have not been identified, this is not likely given the widespread coverage of spectral analyses and the significant exposures of subsurface materials that have been exposed from depths as great as 10 km or more.

*Adsorbed gas.* Adsorbed gas consists of molecules that have diffused into the subsurface and become physically bonded to grain surfaces. The amount available depends on grain composition, particle size, and structure. Best-case calculations show that the regolith can store large quantities of $CO_2$, whether the regolith is basalt or altered clays [6]; however, very little of this $CO_2$ can be emplaced back into the atmosphere under realistic climate conditions, as discussed below and by Mckay et al. [1].

*Loss to space.* Gas can be lost to space by a large number of both thermal (for H) and non-thermal mechanisms. Isotopic enrichment of the heavier isotope in the H, C, N, and Ar systems, seen in meteorite and *in situ* analyses, are all consistent with loss of a significant fraction of gas to space [7, 8]. Recent MAVEN analyses suggest that the bulk of any early thick atmosphere has been lost to space [5]. Once lost, it is no longer available to put back into the atmosphere and contribute to greenhouse warming.

**Greenhouse Warming:** We examine how much $CO_2$ could be emplaced into the atmosphere and on what timescales, and what the resulting greenhouse warming would be.

*Emplacement into the atmosphere.* $CO_2$ that has been lost to space is not available to put back into the atmosphere. If most of the early thick atmosphere has escaped to space, that will limit the atmospheric gas available today.

Polar $CO_2$ is the most accessible reservoir today and polar ice conceivably could be released relatively quickly (e.g., by covering the polar deposits with dust or soot and letting them sublimate in their entirety). However, the total available amospheric pressure is small. Additionally, once in the atmosphere, it likely would be removed quickly, either by diffusion into the subsurface and adsorption or by re-condensing onto the polar caps.

Carbonate could be released only by heating the minerals to their decrepitation temperature, typically above $300^{o}C$. While doable in small quantities, processing any globally distributed carbonates and releasing $CO_2$ into the atmosphere is not feasible. Furthermore the low abundance of accessible carbonates limits the potential atmospheric contributions.

Adsorbed gas can be released by heating. However, increasing the temperature will result in establishment of a new equilibrium between gas-phase and adsorbed gas, without producing a dramatic change in atmospheric pressure [1]. Additionally, any gas released requires heating the subsurface first.

*Net greenhouse warming.* The $CO_2$ available for emplacement into the atmosphere is exceedingly small. Only the polar $CO_2$ ice is readily accessible. Even if a large non-polar subsurface reservoir of carbonates or adsorbed gas were available, it could only be released by heating the materials; global heating would require raising the surface temperature and allowing heat to conduct into the subsurface, an inherently long-term process. Adsorbed gas could be released, but would be limited by the establishment of a new equilibrium between the pore/atmospheric gas and adsorbed gas.

The amount of warming that could be produced today by putting even 100 mbar of $CO_2$ into the atmosphere is small, roughly of order 10 K [2]. The surface or atmospheric temperature required to allow liquid water to exist has not been determined, and liquid water conceivably could exist when atmospheric temperatures are as low as ~245K. However, a warming of 10 K is much less than thought necessary in order to produce liquid water.

**Conclusions:** The ability to release enough $CO_2$ into the Mars atmosphere to provide any significant greenhouse warming is extremely limited. This is the case even if most of the $CO_2$ present on early Mars still remained on the planet, locked up in adsorbed gas and carbonates. Greenhouse warming is further limited in the likely event that the bulk of the early $CO_2$ has been lost to space, as suggested by recent measurements.

While greenhouse warming is still conceivable by the mechanism described by McKay et al. [1], large-scale manufacturing of chlorofluorocarbons, that approach is very far into the future at best.

It is not feasible today, using existing technology or concepts, to carry out any activities that significantly increase the atmospheric $CO_2$ pressure and/or provide any significant warming of the planet. Terraforming in the near term is not feasible.

**References:**

[1] McKay et al., *Nature*, **352**, 489-496, 1991. [2] Kasting, *Icarus*, **94**, 1-13, 1991. [3] Edwards and Ehlmann, *Geology*, doi: 10.1130/G36983.1, 2015. [4] Phillips et al., *Science*, doi: 10.1126/science.1203091, 2011. [5] Jakosky et al., LPSC abstract, 2017. [6] Fanale et al., *Icarus*, **50**, 381-407, 1982. [7] Mahaffy, *Science*, **341**, 263-266, 2013. [8] Jakosky and Phillips, *Nature*, **412**, 237-244, 2001.