MAVEN OBSERVATIONS OF MARS ATMOSPHERIC LOSS AND IMPLICATIONS FOR LONG-TERM EVOLUTION. B. M. Jakosky[1] and the MAVEN Science Team, [1]Laboratory for Atmospheric and Space Physics, Univ. of Colorado, Boulder, CO 80303 (bruce.jakosky@lasp.colorado.edu).

Introduction: The *Mars Atmosphere and Volatile Evolution* (MAVEN) mission is examining the Mars upper atmosphere, its interactions with the Sun and the solar wind, and the ability of these to drive loss of atmospheric gas to space [1]. MAVEN recently completed one Mars year of observations, allowing a determination of loss to space that spans all Mars seasons and includes the effects of solar storms. These results are used as input into extrapolation to long timescales, allowing a preliminary determination of the integrated loss of gas to space through time.

Observations: MAVEN makes observations of the basic structure and composition of the upper atmosphere. Together with the solar energetic inputs in the form of EUV photons, the solar wind, and energetic particles, during both quiescent times and solar storms, and their interactions with the upper atmosphere, we are able to determine their collective ability to drive escape. Rather than walk through the individual observations here, we will focus on the different loss processes and how our understanding is informed by the measurements, on the current loss rates, and on the integrated loss to space through time. We recognize that the extrapolation to total loss involves assumptions regarding upper-atmosphere composition and structure and on the behavior of processes at different epochs. We'll focus here on loss of H and O, as these come from the climate-related species H_2O and CO_2; MAVEN results also relate to loss of other species by a number of different processes.

Jeans' escape. The high-energy tail of the distribution of H atoms that come from atmospheric H_2O can escape thermally. Observations of the H distribution come from the IUVS, SWIA, STATIC, and MAG instruments. The primary observations come from IUVS, with profiles of H in the extended corona allowing calculation of the loss rate. The loss rate is observed to vary by about 10x with season, with the vertical distribution of water (controlled by atmospheric temperatures and dust) being the likely controlling factor. Integration over time is difficult because of the uncertainty in the controlling physics. If the present-day escape rate operated for 4 b.y., it would result in loss of the equivalent of 2-15 m H_2O (global equivalent layer). Actual loss could be an order of magnitude greater than this [2, 3, 4].

Oxygen ion loss. Oxygen ions are lost due to interactions with the solar wind by pickup and other processes. Electric fields accelerate the ions, allowing them to be removed if they reach the escape speed and are suitably directed. Ion escape rates are measured with the STATIC instrument by counting upward- and downward-moving ions. This requires integration over the full mission to get full 4π solid angle coverage as the orbit precesses. Escape is observed to occur largely in a polar plume and down the Martian magnetotail. The present-day loss occurs at a rate sufficient to remove the present-day atmospheric O (present mainly in CO_2) in about 2 b.y. Loss is expected to have been greater when the solar EUV and solar wind were greater early in Mars' history, with the result that integrated loss through time may have removed as much as 0.4 bar CO_2 [5, 6, 7, 8, 9].

Pick-up-ion sputtering. Ions created in the extended oxygen corona upstream of the planet can be accelerated by the solar wind electric field and impact into the upper atmosphere. These ions are capable of physically knocking other atoms and molecules out, in a process called sputtering. MAVEN measures the composition of the incoming ions and their energy (velocity) spectrum, and the properties of the sputtering "target" of the upper atmosphere. We do not measure escaping heavy neutrals, and rely on models to determine the sputtering yield and hence the escape flux for this process. The current estimated loss rate is very small (equivalent to a few mbar over time), but the loss rate again would have been greater early in history. Integrated loss of O due to sputtering could have come from approximately 0.6 bar CO_2 [10, 11, 12].

Photochemical loss of O. Recombination of e^- and O_2^+ in the ionosphere releases sufficient energy to split the O_2 molecule, with ~74% of the O atoms having sufficient residual kinetic energy to escape to space if they are traveling upward and don't collide with anything else first. MAVEN data allow derivation of the dissociative recombination rate orbit-by-orbit from measurements of ionospheric ions, electrons, and electron temperature. We use several different photochemical and hot-O transport models to derive the loss rates. The extrapolation back in time is based largely on the greater solar EUV flux that controls the ionosphere. Extrapolating gives us a total loss through time of the O from ~0.7 bar of CO_2. However, loss could be limited by the changing response of exospheric composition to the increased EUV flux, which may limit the total loss to a much lower value [13, 14, 15].

Loss during solar storms. Enhanced loss via a combination of these processes could occur as a result of the interaction of ICMEs (interplanetary coronal mass ejections) and SIRs (solar interaction regions) with the ionosphere and magnetosphere. The largest ICME event seen by MAVEN occurred on 8 March 2015, but numerous smaller events have been seen. Interpretation of loss is difficult due to the limited geographic coverage for any one event and the limited sampling of event sizes (they can be much stronger than the 8 March event), and statistical analysis is ongoing. Loss rates during the 8 March event are thought to have been roughly 20x as great as the pre-event loss rate, based on a combination of observations and models that can determine loss in all directions. The much higher ICME and SIR occurrence rate early in solar history, inferred from studies of Sun-like stars, may have meant that there were continual/continuous events hitting Mars, and the higher loss driven by storm conditions may have dominated the total loss [9, 16].

Loss derived from isotopic measurements. Gases in the upper atmosphere each have their own scale height above the homopause due to the long mixing times. As a result, removal of gas to space from the exobase preferentially takes the lighter isotope in any isotopic pair, leaving the atmosphere enriched in the heavier one. Measurement of this fractionation allows determination of the fraction of gas lost to space through time. We use Argon, as it doesn't react chemically, so $^{38}Ar/^{36}Ar$ enrichment is a strong indicator of loss to space by the physical sputtering process. Analysis of the MAVEN observations of upper-atmospheric fractionation, combined with MSL measurements of total enrichment, indicate that ~66 % of Ar has been removed to space. This represents a time-integrated, spatially integrated total loss. That loss to space has been an important process is consistent with measurements of isotopic enrichment in atmospheric D/H, $^{15}N/^{14}N$, and $^{13}C/^{12}C$, as measured by MSL and others [17, 18, 19].

Synthesis and conclusions: Loss of O to space by a number of different processes has played a major role in Mars atmosphere evolution. The total amount of O lost is equivalent to either 0.1 to a couple of bars of CO_2 or 2-40 m (GEL) H_2O, or to a combination of these end-members. The isotopic information provides direct evidence that loss was not entirely by either end-member and that significant quantities of both water and carbon dioxide have been lost to space.

We conclude that loss of atmospheric gas to space has been a significant process in the evolution of the Mars atmosphere. It likely was *a* major process for changing Mars from having an early warm, wet climate to the cold, dry climate we see today, and may have been *the* major process. The timing of atmospheric loss is consistent with inferences from the planet's geomorphology.

References: [1] Jakosky et al., Space Sci. Rev., 2015. [2] Chaffin et al., 2015, 2016. [3] Clarke et al., 2016. [4] Bhattacharyya et al., 2016. [5] Brain et al., 2015, 2016. [6] Y. Dong et al., 2015, 2016. [7] Ma et al., 2016. [8] C. Dong et al., 2016. [9] Jakosky et al., Science, 2015. [10] Leblanc et al., 2015. [11] Luhmann et al., 2015, 2016. [12] Y. Dong et al., 2016. [13] Lillis et al., 2016. [14] Deighan et al., 2016. [15] Fox et al., 2015, 2016. [16] Curry et al., 2016. [17] Jakosky et al., 2016. [18] Mahaffy et al., 2015, 2016. [19] Benna et al., 2016.