LOSS OF THE EARLY MARS ATMOSPHERE TO SPACE DETERMINED FROM MAVEN OBSERVATIONS OF THE UPPER ATMOSPHERE. B. M. Jakosky$^1$ and the MAVEN Science Team, $^1$Laboratory for Atmospheric and Space Physics, University of Colorado at Boulder, USA (bruce.jakosky@lasp.colorado.edu).

Introduction: There is compelling evidence that liquid water was abundant on early Mars, despite Mars being too cold today to sustain significant amounts of liquid water. The most likely explanation, especially in the face of the Sun having been dimmer early in its history, is that early Mars had a more-effective greenhouse atmosphere. Measurements from spacecraft and from the surface over the last several decades indicate that there are insufficient carbonate deposits to hold enough CO$_2$ from this early, thicker atmosphere to provide significant warming, however. In that context, the Mars Atmosphere and Volatile Evolution (MAVEN) mission was designed to explore in detail the loss of gas to space occurring at the present epoch; this would allow determination of the integrated loss to space through time and the ability of loss to space to explain the changes inferred for the Martian climate. We report here the loss rates derived through a full Mars year of MAVEN observations, and use these loss rates to extrapolate back in time to get the time-integrated loss to space. These will allow us to determine the role that loss to space played in the changes inferred for the Martian climate. We report here the loss rates derived through a full Mars year of MAVEN observations, and use these loss rates to extrapolate back in time to get the time-integrated loss to space. These will allow us to determine the role that loss to space played in the changes inferred for the Martian climate.

MAVEN has been observing the Mars upper atmosphere, ionosphere, and magnetosphere, along with the solar and solar-wind energetic inputs into the system. The goals are to determine the composition, structure, and behavior of the system and how they are controlled by the energetic drivers, the current rates of loss to space and how they are controlled by the energetic drivers, and properties that allow us to determine the integrated loss to space through time. MAVEN has been making science observations for more than a full Mars year.

Results: MAVEN observations have been used to derive the rates of loss of gas to space, as follows:

Hydrogen loss. Hydrogen is created in the upper atmosphere from the photodissociation of H$_2$O in the lower and middle atmosphere and the transport of the H upward. The H atom is light enough that those atoms in the high-energy tail on the Boltzmann distribution and residing above the nominal exobase will have enough energy to escape to space. This thermal (or Jeans) escape is likely to be the main mechanism by which H is lost to space. The combination of escaping atoms and atoms having sufficient energy to travel ballistically to high altitudes but not to escape creates an extended corona of H atoms surrounding Mars; this corona can extend out past 10 R$_M$ or greater.

For the range in observed column abundance and temperature of H in the corona, the loss rate is inferred to vary with season during the Mars year between $\sim$1-11 x 10$^{26}$ H s$^{-1}$. This is equivalent to a loss rate of $\sim$160-1800 g H s$^{-1}$. At this rate, the entire column of atmospheric water at present (nominally, about 10 precipitable micrometers, or 10$^{-3}$ g/cm$^2$) would be removed in between ~3000 - 30,000 years. Over 4 b.y., loss at this rate would be able to remove a global layer of water between ~3-24 m thick.

Oxygen ion loss. Ion loss occurs via the acceleration of ions in an electric field. The electric field can be generated by the moving magnetic field of the impinging solar wind or by the motion of ions around the magnetic field in magnetic cusp regions associated with the crust.

The integrated escape is obtained by summing up the loss across the planet, breaking the loss into separate O$^+$ and O$_2^+$ rates. The net global loss rate for O is 5 x 10$^{24}$ s$^{-1}$, equivalent to a loss rate of $\sim$130 g O s$^{-1}$. If loss occurred at this constant rate, the entire column of atmospheric O (present mainly as CO$_2$) would be removed in 3 b.y.

Photochemical loss. Photodissociation can ionize O$_2$ or N$_2$. When the electrons and ions recombine, the energy is released via one of multiple pathways. In some of the recombinations, the energy is sufficient both to break the O$_2$ bond and to give each of the resulting O atoms an amount of energy (as kinetic energy) greater than the escape energy from Mars; when recombination occurs above the exobase, such that the upward-moving atom will not hit anything, it will escape to space.

MAVEN does not measure the escaping neutral O atoms. But it does measure the upper-atmospheric ion composition and electron properties, allowing the photodissociation and recombination rates and the resulting escape rate to be calculated. The loss rate can be calculated for each orbit. The derived loss rate varies dramatically through the mission due to the precession of the orbit, with geographic location, solar zenith angle, and local time all varying. Values calculated where measurements are made on the night side of the planet, for example, are extremely low due to the extremely tenuous ionosphere there. Loss rates on the
day side, where the ionosphere is significant, are greater.

The average O loss rate inferred from these observations is \(5 \times 10^{25} \text{ O s}^{-1}\), equivalent to 1300 g O s\(^{-1}\). At this rate, the O present as CO\(_2\) in today’s atmosphere would be lost in 300 m.y.

**Sputtering loss.** The electric field generated by the solar wind will accelerate ions in one hemisphere (relative to the magnetic field) away from the planet causing them to escape, and from the other hemisphere into the planet where they collide with molecules in the upper atmosphere. When these ions collide at high velocities (up to twice the solar-wind velocity, or nearly 1000 km/s), they can physically knock upper-atmospheric constituents out of the atmosphere. This sputtering process can be very effective in removing neutral atoms (and is the only significant mechanism for removing species such as argon, which is a noble gas). MAVEN does not measure escaping neutrals. However, we can measure the properties of the incoming ions (composition and speed) and the composition of the upper-atmospheric target onto which they impinge. From these, we can calculate the sputtering loss yield based on well-developed theories of sputtering.

For the coverage obtained during the year of observations, the average loss rate is \(3 \times 10^{24} \text{ O s}^{-1}\), equivalent to \(80 \text{ g O s}^{-1}\). At this loss rate, it would take more than 4 b.y. to remove the atmospheric column of O.

**Integrated loss rates.** We can sum up the loss as observed or inferred during this one Mars year. The loss of H, over 4 b.y., would result in loss of an equivalent of a global layer of H\(_2\)O between 3 – 24 m thick.

The total loss rate of O at present is \(6 \times 10^{25} \text{ O s}^{-1}\). At this rate, the present column of atmospheric O would be lost in about 250 m.y.; equivalently this would remove a total of \(75 \text{ mbar of CO}_2\) over 4 billion years.

**Extrapolation back in time.** These rates are not expected to have been constant in time. The major factors that were different early in Mars history were the EUV flux from the Sun and the nature of the solar wind. These were recognized as being important drivers of the escape rate by each of the above processes by Luhmann et al. (1992), and the extrapolations to early times indicated that loss rates could have been orders of magnitude greater than they are today. These models have been updated as our understanding of the evolution of sun-like stars and of the escape processes themselves have improved. We use the most recent integrated model, that of Chassefiere and Leblanc (2013), to extrapolate back in time.

When integrated through time, the integrated loss of O is equivalent to loss of greater than 0.5 bar of CO\(_2\), 15 m global equivalent layer of water, or some combination of the two depending on the source of the O. Our extrapolation makes these numbers a conservative estimate, with the actual loss possibly being considerably larger.

Loss of H is more difficult to extrapolate into the past. One issue is that we do not as yet fully understand what drives the seasonal behavior of the abundance of H in the corona and of the escape rate. While the suggestion of dust allowing H\(_2\)O to rise higher during southern summer and be photodissociated closer to the exobase is plausible, it has not been cleanly demonstrated. Even if it is correct, we do not as yet understand the seasonal variability in either the dust cycle or the lower-atmosphere water cycle well enough to determine whether the year observed by MAVEN is representative of the current epoch, or even whether the extreme high or low values of H escape rate might be representative.

Even if we understood the present-day H loss rate, it would be difficult to extrapolate to ancient times. On the one hand, loss could have been greater in ancient times than it is today based on the increased solar EUV flux. The EUV would have provided additional heating of the upper atmosphere, increasing the H escape rate. On the other hand, loss of H could have been less in ancient times if, by having a more-Earth-like atmosphere, the Martian middle atmosphere had a more-efficient cold trap that kept the H\(_2\)O from getting as high in the atmosphere.

**Conclusions:** Combined with the previous results on loss derived from the Ar isotopes (Jakosky et al., 2017), these results provide a direct indication that the bulk of the early Martian atmosphere has been lost to space. The timing of this loss as determined from the history of the Sun is consistent with that inferred from the geology of the surface. Combined with the lack of evidence for a substantial CO\(_2\) reservoir on the surface or in the subsurface, we conclude that loss to space was the major process by which the Mars atmosphere evolved from an early, warmer and wetter climate to the cold, dry climate that we see today.