Modeling of Ion and Photochemical Losses to Space over the Martian History: Implications for Exoplanetary Climate Evolution and Habitability. C. F. Dong\textsuperscript{1}, Y. Lee\textsuperscript{2}, Y. J. Ma\textsuperscript{3}, S. W. Bougher\textsuperscript{4}, J. G. Luhmann\textsuperscript{5}, B. M. Jakosky\textsuperscript{6}, S. M. Curry\textsuperscript{3}, D. A. Brain\textsuperscript{6}, G. Toth\textsuperscript{6}, and A. F. Nagy\textsuperscript{4}, \textsuperscript{1}Princeton University (defy@princeton.edu), \textsuperscript{2}NASA GSFC, \textsuperscript{3}IGPP, UCLA, \textsuperscript{4}CLaSP, University of Michigan, \textsuperscript{5}SSL, UC Berkeley, \textsuperscript{6}LASP, CU-Boulder

\textbf{Introduction:} Mars may have had a thicker atmosphere and liquid water on its surface between 3.5 and 4 billion years ago. However, today’s Red Planet has dry and cold surface environments and a small surface pressure (~6 mbar) mainly resulting from the thin and cold atmosphere. So one of the most important questions is: where did all of the atmosphere and liquid water go? One of the MAVEN’s primary objectives is to quantify the atmospheric escape to space over time [e., \textsuperscript{1,2}]. In order to understand the effect of atmospheric losses to space on the long-term evolution of the Martian atmosphere (e.g., loss of water) and its climate change over its history, the well-validated 3-D state-of-the-art numerical tools are essential to study both the ion and photochemical escape back to 4 billion years ago.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{A sketch of a one-way coupling approach between M-GITM, M-AMPS, and MHD \textsuperscript{4}. The notation \( T_n \) denotes neutral atmosphere temperatures, and \([O], [CO_2], \) and \([O_{\text{hot}}]\) are the neutral O, CO\textsubscript{2}, and hot atomic oxygen number densities, respectively.}
\end{figure}

\textbf{Method:} In this study, we adopted the one-way coupled framework (Fig. 1) which has been employed to study the ion and photochemical losses at the current epoch \textsuperscript{[3,4]}. We adopted the 3-D Mars thermosphere (i.e., neutral temperatures \( T_m \), neutral densities \([O], [CO_2], \) and photoionization frequencies \( I_0, I_{CO_2} \) from the Mars Global Ionospheric Thermosphere Model (M-GITM) \textsuperscript{5} and the hot atomic oxygen density, \([O_{\text{hot}}] \), from the Mars exosphere Monte Carlo model Adaptive Mesh Particle Simulator (M-AMPS) \textsuperscript{3}. These neutral profiles are one-way coupled with the 3-D BATS-R-

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Calculated ion and photochemical escape rates over the Martian history.}
\end{figure}

\textbf{Results:} Fig. 2 presents the calculated ion (solid lines) and photochemical (dashed line) escape rates by using this one-way coupled framework (Fig. 1) over the Martian history. In Fig. 2, the \( O^+ \) ion loss dominates over heavy ion species (\( O_2^+ \) and \( CO_2^+ \)) at early Mars and the corresponding \( O^+ \) ion escape rate is much higher than the current value. Although the photochemical escape is the dominant loss mechanism at current Mars, the total ion escape rate is much higher than the photochemical escape rate at early Mars.

In summary, this study informs our understanding of the long-term evolution of the Martian climate due to atmospheric losses to space, and has implications for analogous change on exoplanets. Thus, it offers fresh insights concerning the habitability of the increasing number of exoplanets discovered yearly.